INTERIM REPORT: VOC AND ALDEHYDE EMISSIONS IN FOUR FEMA TEMPORARY HOUSING UNITS

Randy L. Maddalena, Marion Russell, Douglas P. Sullivan, and Michael G. Apte

Indoor Environment Department
Lawrence Berkeley National Laboratory

4 May, 2008

This work was supported by interagency agreement 08FED894632 from CDC – NCEH and also the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of CDC –NCEH or US DOE.

ABSTRACT

Four unoccupied FEMA temporary housing units (THUs) were studied to assess their indoor emissions of volatile organic compounds including formaldehyde. Measurement of whole-THU VOC and aldehyde emission factors (μg h^{-1} per m^2 of floor area) for each of the four THUs were made at FEMA's Purvis MS staging yard using a mass balance approach. Measurements were made in the morning, and again in the afternoon in each THU. Steady-state indoor formaldehyde concentrations ranged from 378 μg m^{-3} (0.31ppm) to 632 μg m^{-3} (0.52 ppm) in the AM, and from 433 μg m^{-3} (0.35 ppm) to 926 μg m^{-3} (0.78 ppm) in the PM. THU air exchange rates ranged from 0.15 h^{-1} to 0.39 h^{-1}. A total of 45 small (approximately 0.025 m^2) samples of surface material, 16 types, were collected directly from the four THUs and shipped to Lawrence Berkeley Laboratory. The material samples were analyzed for VOC and aldehyde emissions in small stainless steel chambers using a standard, accurate mass balance method. Quantification of VOCs was done via gas chromatography – mass spectrometry and low molecular weight aldehydes via high performance liquid chromatography. Material specific emission factors (μg h^{-1} per m^2 of material) were quantified. Approximately 80 unique VOCs were tentatively identified in the THU field samples, of which forty-five were quantified either because of their toxicological significance or because their concentrations were high. Whole-trailer and material specific emission factors were calculated for 33 compounds. The THU emission factors and those from their component materials were compared against those measured from other types of housing and the materials used in their construction. Whole THU emission factors for most VOCs were typically similar to those from comparative housing. The three exceptions were exceptionally large emissions of formaldehyde and TMPD-DIB (a common plasticizer in vinyl products), and somewhat elevated for phenol. Of these three compounds, formaldehyde was the only one with toxicological significance at the observed concentrations. Whole THU formaldehyde emissions ranged from 173 to 266 μg m^{-2} h^{-1} in the morning and 257 to 347 μg m^{-2} h^{-1} in the afternoon. Median formaldehyde emissions in previously studied site-built and manufactured homes were 31 and 45 μg m^{-2} h^{-1}, respectively. Only one of the composite wood materials that was tested appeared to exceed the HUD formaldehyde emission standard (430 μg/m^2 h^{-1} for particleboard and 130 μg/m^2 h^{-1} for plywood). The high loading factor (material surface area divided by THU volume) of composite wood products in the THUs and the low fresh air exchange relative to the material surface area may be responsible for the excessive concentrations observed for some of the VOCs and formaldehyde.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The objectives of this study have been to 1) directly measure indoor concentrations and whole trailer emission factors in four unoccupied temporary housing units (THUs) for a range of volatile organic compounds (VOCs) and aldehydes including formaldehyde, and 2) determine materials specific emission factors of these compounds from individual surface materials collected directly from the THUs providing initial information into the magnitude and potential sources of indoor pollutant loadings in the tested THUs.

The Federal Emergency Management Administration (FEMA) has supplied over 100,000 emergency THUs to families that lost their homes in Louisiana and Mississippi during the Hurricane Katrina and Rita disasters. FEMA owns approximately 160,000 of these THUs. Some are deployed to other parts of the U.S., some are used to house emergency workers, and many are in storage. Concerns about the indoor environmental quality in the THUs have arisen based on occupant health complaints and problems. These problems have been identified by physicians treating THU occupants, and through risk analyses of indoor air quality measurements made in both occupied and unoccupied units. These measurements were reported by the Sierra Club and by the Centers for Disease Control. Of utmost concern is that measured formaldehyde concentrations observed in both occupied and unoccupied THUs have exceeded the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit of 0.016 ppm, often by a factor of 10 or greater.

Measured emission factors for individual building materials can be used to assess the contribution of specific materials to the overall indoor pollutant load using mass balance modeling. Emission factors describe the mass of a particular compound emitted by a material per hour, per unit area. Measured emission factors provide a means to directly compare emission characteristics from one material to another. Emission factors from materials are dependent on a range of environmental parameters such as temperature, relative humidity and boundary layer diffusion characteristics, which are influenced by air flow across the surface. It is important that these parameters are consistent when emission factors are compared.

When describing emissions from a single material, i.e., fiberboard or flooring, emission factors are typically expressed in terms of the projected surface area of the material itself. However, when describing the emissions from a composite assembly of materials, such as a house or travel trailer that is composed of a variety of component pieces, it is difficult to isolate a single emission source. In this case, it is customary to present emissions of a particular compound as a net mass emitted per unit area of floor, per hour. Both of these emission factor metrics have the same units: $\mu g\ m^{-2}\ h^{-1}$. It is important to understand the distinction between emissions on a per-material area versus a net per-floor area basis when studying material emission characteristics.

Sources contributing to elevated formaldehyde indoors are primarily related to building products and furnishings. Formaldehyde is only one compound of concern that is emitted from these materials. A range of volatile organic compounds (VOCs) typically present when formaldehyde is observed, are also emitted from materials. Like formaldehyde, which is a toxic air contaminant, many of the VOCs are known to have low odor thresholds, high potency as respiratory irritants, and in some cases carcinogenicity.

in this study, four unoccupied FEMA temporary housing units (THUs) were studied to assess their indoor emissions of volatile organic compounds including formaldehyde. First, whole-THU emissions were measured, and then selected material samples were collected from the four units and their material specific emission rates were measured in small chambers. Standard analytical methods employing rigorous quality control were used to quantify VOC and aldehyde compound mass collected on air sampling media in the whole-THU and chamber emissions measurements.

The THUs selected for study included a Thor Industries Dutchmen manufactured September 2005, a Pilgrim International manufactured October 2005, a Coachmen's Spirit of America manufactured October 2006 and a Gulfstream Coach Cavalier manufactured March 2006. The units were in excellent condition. The approximate floor areas ranged from 221 – 240 square feet. The Dutchman trailer was equipped with an additional pullout section approximately 14 feet long by 3 feet (~42 ft^2) that was not opened up during sampling.

Measurement of whole-THU VOC and aldehyde emission factors ($\mu g\ h^{-1}$ per m^2 of floor area) for each of the four THUs were made at FEMA's Purvis MS staging yard using a mass balance approach. Measurements were made in the morning, and again in the afternoon in each THU. Steady-state indoor formaldehyde concentrations ranged from 378 $\mu g\ m^{-3}$ (0.31ppm) to 632 $\mu g\ m^{-3}$ (0.52 ppm) in the AM, and from 433 $\mu g\ m^{-3}$ (0.35 ppm) to 926 $\mu g\ m^{-3}$ (0.78 ppm) in the PM. THU air exchange rates ranged from 0.15 h^{-1} to 0.39 h^{-1}.

A total of 45 small (approximately 0.025 m^2) samples of surface material, 16 types, were collected directly from the four THUs and shipped to Lawrence Berkeley Laboratory. Material specific emission factors were determined using small chambers generally following the ASTM Standard Guide D-5116-97. The material samples were analyzed for VOC and aldehyde emissions in small stainless steel chambers using a standard, accurate mass balance method. Quantification of VOCs was done via gas chromatography – mass spectrometry and low molecular weight aldehydes via high performance liquid chromatography. Material specific emission factors ($\mu g\ h^{-1}$ per m^2 of material) were quantified. Approximately 80 unique VOCs were tentatively identified in the THU field samples, of which forty-five were quantified either because of their toxicological significance or because their concentrations were high.

All THUs had a significant fraction of the internal surface area (walls, ceiling, cabinet walls) constructed of 1/8-inch plywood with a vinyl or PVC skin or simulated wood finish. All units had sheet vinyl flooring while the Dutchmen and Pilgrim also had carpeted areas. All countertops were particleboard surfaced with high-pressure laminate. A variety of wood products were used for the sub-floor and for the bench and bed platforms.

Whole-trailer and material specific emission factors were calculated for 33 compounds. The THU emission factors and those from their component materials were compared against those measured from other types of housing and the materials used in their construction. Whole THU emission factors for most VOCs were typically similar to those from comparative housing measured in the U.S (all approximately 6 months old or less). Three exceptions were exceptionally large emissions of formaldehyde and TMPD-DIB (a common plasticizer in vinyl products), and somewhat elevated for phenol. Of these three compounds, formaldehyde was the only one is thought to be of toxicological significance at the observed concentrations.

Additionally, several VOCs (dodecane, tridecane, p-xylene, alpha-pinene, beta-pinene and hexanal) were measured in the four THUs at concentrations above those reported in a study of 39 German homes.

Whole THU formaldehyde emissions ranged from 173 to 266 $\mu g\ m^{-2}\ h^{-1}$ in the morning and 257 to 347 $\mu g\ m^{-2}\ h^{-1}$ in the afternoon. Median formaldehyde emissions in previously studied site-built and manufactured homes (approximately 6 months old or less) were 31 and 45 $\mu g\ m^{-2}\ h^{-1}$, respectively.

The material specific formaldehyde emission factor measurements showed that the highest material emissions were from the cabinet walls, sub flooring, and the bench materials (the fabric and foam materials also showed elevated emissions, but these are likely due to the re-emission of formaldehyde that had sorbed to the material from the indoor air, rather than as primary emitters). Only one material, the Cavalier plywood cabinet wall (490 $\mu g\ m^{-2}\ h^{-1}$) exhibited emissions in excess of the HUD standard of 130 $\mu g\ m^{-2}\ h^{-1}$.

Formaldehyde emission factors from the various composite wood materials appear to be well within the range found in previously published research although significant differences can be expected due to the aging of the material in the THUs. Therefore, it is difficult to conclude that these materials would have been within previously reported ranges had the tests been conducted using fresh materials. In contrast, the emission factors for phenol, TMPD-DIB, and formaldehyde remained higher in the THUs than the new homes.

Thus, whole trailer formaldehyde emission factors are high, but the materials emission factors may be within those commonly found in the building industry. This indicates a difference in the construction/design that may lead to elevated concentrations and whole trailer emission rates. Three features of material application in the THUs differ from most other dwellings: 1) the extensive use of lightweight composite wood products, 2) very high surface loading of composite wood products and 3) low fresh air per unit surface area of composite wood products in the THUs.

Much of the projected surface area in the THUs (wall, ceiling, and cabinetry) use 1/8" plywood. These materials are used presumably to reduce weight relative to the gypsum board material used in conventional houses. Almost all surfaces in these structures are wood. The wood product loading factor of the THU is far higher than in housing that uses gypsum for walls and ceilings. The combination of these factors is likely to be the cause of the unusually high rates at which formaldehyde mass is emitted into the THU. Considering this in terms of the area-specific clean air flow rates, the high material loading ratio in the units combined with relatively low fresh air ventilation rates results in area-specific air flow rates that are quite low relative to other housing types. With all other factors being equal, the steady-state concentrations indoors are inversely proportional to the air exchange rates. The THUs in this study are not outfitted for adequate ventilation and are tighter than would be desired for housing with such small volume. Although low ventilation does not directly affect the measured formaldehyde emission rates presented in this report, it can influence the concentrations experienced by occupants, the issue of greatest concern.

In conclusion, a large number of THUs are owned by the Federal Emergency Management Administration. Although it may not be scientifically defensible to develop a judgment regarding the entire fleet of THUs based on the measurements of the convenience sample of four units presented in this study, the measured material-specific emission factors for volatile organic compounds, including formaldehyde, were not atypical relative to the literature for materials. However, it is important to consider that the materials in this study were both aged and allowed to interact with emissions from other materials. Formaldehyde and some of the other VOCs measured in the unoccupied THUs and the associated whole trailer emission factors were found to be higher, sometimes much higher, than what is typically found in residential environments. The difference between these THUs and other housing appears to be the very high composite wood surface area relative to room volume used in the travel trailer design and the low ventilation rates in terms of low area-specific fresh air flow rates in the THUs.

Recommendations for future work

This interim report provides a preliminary assessment into the effect of THU design and material choices on indoor VOC and aldehyde concentrations. It is by no means definitive, as a convenience sample of only four THU models produced by four manufactures was evaluated. Additionally, the focus of this study was on the travel trailers, while a significant portion of THUs are park trailer models, and mobile homes. A systematic assessment across a wider range of THU makes and models including a better characterization of fresh air ventilation rates under occupied conditions could provide a better understanding of the time integrated exposure concentrations in occupied units.

The results in this report do not yet address temperature and humidity effects on material emissions within the studied units. It is hypothesized that at the higher temperature and relative humidity conditions found in the summertime in the southeastern portions of the US, emissions of formaldehyde from the urea-formaldehyde composite woods will increase. Chamber experiments and a seasonal study designed to investigate the potential effects of temperature and humidity should be completed.

INTRODUCTION

The Federal Emergency Management Administration (FEMA) has supplied over 100,000 emergency temporary housing units (THUs) to families that lost their homes in Louisiana and Mississippi during the Hurricane Katrina and Rita disasters. FEMA owns approximately 160,000 of these THUs. Some are deployed to other parts of the U.S., some are used to house emergency workers, and many are in storage. Concerns about the indoor environmental quality in the THUs have arisen based on occupant health complaints and problems. These problems have been identified by physicians treating THU occupants, and through risk analyses of indoor air quality measurements made in both occupied and unoccupied units. These measurements were reported by the Sierra Club and by the Centers for Disease Control. Of utmost concern is that measured formaldehyde concentrations observed in both occupied and unoccupied THUs have exceeded the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit of 0.016 ppm, often by a factor of 10 or greater.

Although formaldehyde levels in the THUs was highlighted by the Sierra Club survey, and by media focus, a concern has existed that other irritating, odorous, or potentially toxic volatile organic compounds (VOC) may be emitted from the THU construction materials and furnishings, and that the design of the THUs, including extensive used of plywood, particle board and laminated material and low ventilation rates may lead to elevated exposure concentrations. A thorough understanding of the indoor VOC concentrations and emissions from the THU materials was needed to assess this issue.

Emission Factors

Measured emission factors for individual building materials can be used to assess the contribution of specific materials to the overall indoor pollutant load using mass balance modeling (Hodgson et. al., 2004). Emission factors describe the mass of a particular compound emitted by a material per hour, per unit area. Measured emission factors provide a means to directly compare emission characteristics from one material to another. Emission factors from materials are dependent on a range of environmental parameters such as temperature, relative humidity and boundary layer diffusion characteristics, which are influenced by air flow across the surface. It is important that these parameters are consistent when emission factors are compared. Measurement method standardization helps to ensure this.

When describing emissions from a single material, i.e., fiberboard or flooring, emission factors are typically expressed in terms of the projected surface area of the material itself. However, when describing the emissions from a composite assembly of materials, such as a house or travel trailer that is composed of a variety of component pieces, it is difficult to isolate a single emission source. In this case, it is customary to present emissions of a particular compound as a net mass emitted per unit area of floor, per hour. Both of these emission factor metrics have the same units: $\mu g\ m^{-2}\ h^{-1}$. It is important to understand the distinction between emissions on a per-material area versus a net per-floor area basis when studying material emission characteristics. The convention followed in this work is to report whole-trailer emission factors on a floor area basis while the individual materials are reported on a projected surface area basis.

Formaldehyde Emissions From Building Materials – Background Information
Sources contributing to elevated formaldehyde indoors are primarily related to building products and furnishings. Formaldehyde is only one compound of concern that is emitted from these materials. A range of volatile organic compounds (VOCs) typically present when formaldehyde is observed, are also emitted from materials (Hodgson, 1999). Like formaldehyde, which is a toxic air contaminant, many of the VOCs are known to have low odor thresholds, high potency as respiratory irritants, and in some cases carcinogenicity.

The problem of excessive formaldehyde emissions from building materials reached national awareness starting in the early 1980s with the increase in commercial and industrial use of urea formaldehyde as a bonding agent and as an expanded foam insulation (UFFI). The US Consumer Product Safety Commission (CPSC) had reported health complaints caused by UFFI since 1972. In 1980 the National Academy of Science advised maintaining the lowest practical formaldehyde concentrations in order to minimize possible adverse effects on public health, based upon emerging results from an ongoing carcinogenicity study (NAS 1980). A heightened concern began with the emergence of health effects in occupants of mobile homes (Hileman, 1982). In 1982 the Consumer Product Safety Commission placed a ban on UFFI (CPSC 1982). This ban was subsequently lifted a year later by court order (CPSC 1983). However, the use of UFFI as a building material was curtailed by the industry.

In 1984 the U.S. Department of Housing and Urban Development (HUD) established formaldehyde product standards for all plywood and particleboard materials using bonding, coating, or surface finishing systems containing formaldehyde when installed in manufactured homes (Turner et al. 1996). The standard is embodied in the HUD Standard 24 CFR Ch. XX Part 3280, *Manufactured Home Construction and Safety Standards* (HUD 2001). The standard is based upon the ASTM emission testing method E-1333 that continues to be used (ASTM 2002). The standard was intended to cap the mass of formaldehyde that emanated from fresh wood materials in terms of concentration in a test chamber using standardized surface loading ratios and area specific air flows or air exchange rates. The standard was developed for testing newly manufactured wood products prior to their use in construction[1].

The wood products industry adopted the HUD standard in the U.S. during the 1980s. Subsequent surveys indicated that because the reduction of the mass emission rate from wood products and discontinuation of the use of UFFI in residential construction, formaldehyde levels in residences dropped substantially (Azuma et al. 2006) through the 1980s and 1990s.

Formaldehyde Emission Behavior
Past research has established that the rate at which formaldehyde is emitted from some building products drops slowly as the materials ages after manufacture. This concept is often brought up

[1] The HUD safety standards for certified plywood and particleboard used in manufactured home construction require that formaldehyde emissions not exceed 0.2 ppm (0.246 mg/m^3) from plywood and 0.3 ppm (0.369 mg/m^3) from particleboard, as measured by the method specified in ASTM Method E1333. Engineered wood products are tested with specified loading ratios for particleboard and plywood of 0.43 m^2/m^3 (0.13 ft^2/ft^3), and 0.95 m^2/m^3 (0.29 ft^2/ft^3), respectively. Using the operating conditions specified in the standard and the formaldehyde emissions rate equation, formaldehyde emissions rates from the material are 430 $\mu g/m^2/h$ (8.81×10^{-8} $lb/ft^2/h$) for particleboard and 130 $\mu g/m^2 \bullet h$ (2.66×10^{-8} $lb/ft^2 \bullet h$) for plywood.

when the topic of indoor formaldehyde emissions from materials is discussed. The fact is often used to indicate that indoor formaldehyde concentrations will lower with time, lessening risk and health problems. However, the rate at which emissions drops is not well determined and will depend upon many factors. A recently released industry association report (SEFA 2008) concluded that emissions can drop by 25% within a month of manufacture and usually drop by half within six months.

A study of emission characteristics of pressed-wood products conducted by Oak Ridge National Laboratory (ORNL) for the U.S. Consumer Product Safety Commission (Matthews 1985) found that the time needed for emissions to drop to approximately 37% of initial rate was between 0.9 and 2.2 years depending on the material tested. The longer decay period was for a mixture of materials (particleboard underlayment, industrial particleboard, hardwood plywood paneling and medium density fiberboard). The shorter decay periods were associated with weaker board material at lower starting formaldehyde concentrations.

Using the 2.2 year decay rate determined in the ORNL study (Matthews 1985) for materials that are similar to THU materials, and assuming a starting formaldehyde concentration of 300 ppb with an air exchange rate of 0.5 h^{-1} (HUD standard for particle board), the required duration for the concentration in a new trailer to drop to an equilibrium concentration of 10 ppb (similar to background, ASTDR 1999) is 7.5 years. For the lighter materials with the faster decay rate measure by ORNL, and assuming a starting concentration of 200 ppb, the time to reach 10 ppb is between three and five years.

Another key finding in the ORNL study was the effectiveness of vinyl flooring as a barrier in reduction of formaldehyde emission rates. This finding is salient to the THUs studied in this project in that much of the floor area had sheet vinyl covering and the walls, ceiling, cabinets, and doors were also covered with a PVC, photolaminant or vinyl material. The ORNL report found through both modeling and measurements that carpet and cushion covering resulted in approximately a 2.5 fold reduction in formaldehyde emissions while vinyl flooring reduced emission by approximately 30 fold (Matthews 1985).

Other building material studies have reported on the effectiveness or lack of effectiveness of coatings, layers, laminates, and other coverings showing that different coverings retard emissions differently. Some studies have shown that there can be significant sink effects with certain floor and wall covering materials when used in conjunction with other emitting sources highlighting more complex interactions and effects of flooring and wall assemblies including peak VOCs shifts with respect to time instead of simple decays (Won et al. 2001).

Volatile Organic Compound (VOC) Emissions from Building Materials - Background Information

Considerably less information is available on VOC emissions from construction materials other than formaldehyde. Key sources of new information are Hodgson et al. (1999, 2000, and 2004), Hodgson and Levin (2003), the California Integrated Waste Management Board (CIWMB 2003), Hipellein (2004) and Won et.al. (2004). For the purposes of this interim report we are able to make comparisons of residential concentrations and to whole structure VOC emission factors on a per-floor area basis. The sparse data on VOC emissions at the material level make comparisons more tenuous, however, enough data exists to make some qualitative conclusions regarding individual materials' contributions to indoor VOC concentrations in the THUs.

The objectives of this study are to 1) directly measure indoor concentrations and whole trailer emission factors in four unoccupied THUs for a range of VOCs and 2) determine materials specific emission factors from individual surface materials collected directly from the THUs providing initial information into the magnitude and potential sources of indoor pollutant loadings in the tested THUs.

METHODS

Overview of Experimental Approach

Four unoccupied temporary housing units (THUs) each produced by a different manufacturer were selected for study from stock at the FEMA staging yard in Purvis, Mississippi. For each THU, indoor and outdoor air concentrations were determined for a range of pollutants at two separate time points and steady-state ventilation rates were measured. After completion of the whole trailer measurements, representative surface materials were cut directly from each THU, packaged and shipped to Lawrence Berkeley National Laboratory for testing in small chambers to determine material-specific VOC emission factors. The projected surface areas of the materials in the THUs were measured and used along with the emission factors to characterize the relative contributions of the materials to total pollutant loads in the THUs.

Description of Study Units

The THUs selected for study included a Thor Industries Dutchmen manufactured September 2005, a Pilgrim International manufactured October 2005, a Coachmen's Spirit of America manufactured October 2006 and a Gulfstream Coach Cavalier manufactured March 2006. The units were in excellent condition. The approximate floor areas ranged from 221 – 240 square feet. The Dutchman trailer was equipped with an additional pullout section approximately 14 feet long by 3 feet (~42 ft^2) that was not opened up during sampling.

The trailer dimensions and specifications are summarized in Table 1. The Pilgrim and Cavalier trailers were built to FEMA specification while the Dutchmen and Coachmen were built to HUD standards. The units tested were all travel trailer designs that had either not been previously occupied or had been reconditioned and made ready for re-deployment. The projected surfaces areas of each surface material in the THUs are summarized in Table 2. A description of the individual building material types is provided in Table 3 and the surface covering or finishes are summarized in Table 4.

The trailers were moved to a central staging area at the storage yard on November 9, 2007 and were parked in approximately the same directional orientation. A series of small holes (~6 mm) were drilled in the entrance door of each trailer (Figure 1) to allow insertion of rigid stainless steel sampling tubes for sample collection (Figure 2). Rigid sampling tubes were extended approximately 1 meter into a trailer and elevated 1 meter from the floor to facilitate sampling of VOCs, aldehydes, acetic acid, temperature, relative humidity, and tracer gas concentrations without opening the trailer. Mixing fans were installed in each trailer for use only in mixing the injected tracer gas to determine each THU's characteristic air exchange ventilation rates. These fans were not otherwise operated including during VOC sampling.

After initial setup, the trailers were closed and remained closed to allow the ambient ventilation rates to come to steady-state. Sampling was conducted on November 14, 2007. Temperature, relative humidity and CO_2 concentrations were monitored in each trailer and at a central location outdoors during the experiments using calibrated indoor air quality monitors (Q-Trac Plus; TSI).

Air Sampling and Analysis

Volatile Organic Chemicals – VOCs

VOC samples were collected and analyzed following USEPA Methods TO-1 and TO-17 (USEPA 1999). VOCs were collected onto multibed sorbent tubes (P/N 012347-005-00; Gerstel or equivalent) with primary bed of Tenax-TA® sorbent backed with a section of Carbosieve®. Prior to use, the sorbent tubes were conditioned by helium purge (~10 cc/min) at 275 ^{o}C for 60 minutes and sealed in Teflon capped tubes. VOC samples were collected through a rigid stainless steal tube inserted through the trailer door, directly into the tube for outdoor samples, and directly from the exit port in the small emission chamber. A vacuum pump (Model DOA-P104-AA; Gast) with electronic mass flow controllers (lab), or calibrated personal sampler pumps (field) were used to pull air through the sample tubes at ~100 cc/min. Approximately 6 liters were collected from the whole-trailers and 3 liters from the emission chambers. Flows were verified using a separate calibrated flow meter prior to the emission chamber experiments. The personal sampler pumps used in the field were calibrated prior to use and checked after use. Sorbent tubes were sealed with Teflon lined caps after use and either analyzed the same day or stored on ice or in a freezer until analysis. Sample stability over freezer storage times of more than 2 months have been confirmed previously in our lab for many of the VOCs included in this study.

Sorbent tubes were thermally desorbed for analysis by gas chromatography/mass spectrometry (TD-GC/MS) using a thermodesorption auto-sampler (Model TDSA2; Gerstel), a thermodesorption oven (Model TDS3, Gerstel) and a cooled injection system (Model CIS4; Gerstel). The cooled injection system was fitted with a Tenax-packed glass liner (P/N 013247-005-00; Gerstel). Desorption temperature was 25 ^{o}C with a 0.5 minute delay followed by a 60 ^{o}C ramp to 250 ^{o}C and a 4 minute hold time. The cryogenic trap was held at -10 ^{o}C and then heated within 0.2 minutes to 270 ^{o}C at a rate of 12 ^{o}C/s, followed by a 3-minute hold time. Compounds were resolved on a GC (Series 6890Plus; Agilent Technologies) equipped with a 30 meter HP-1701 14% Cyanopropyl Phenyl Methyl column (Model 19091U-233; Agilent Technologies) at an initial temperature of 1 ^{o}C for 0.5 minutes then ramped to 40 ^{o}C at 25 ^{o}C/min, to 115 ^{o}C at 3 ^{o}C/min and finally to 250 ^{o}C at 10 ^{o}C/min holding for 10 minutes.

The resolved analytes were detected using an electron impact MS system (5973; Agilent Technologies). The MS was operated in scan mode. One sample from each trailer was analyzed and all compounds over the detection limit (< 1 to several ng) were identified by library search using the NIST spectral library followed by comparison to reference standards. Multipoint calibrations were prepared from pure standards for 43 VOCs that were common indoor pollutants and/or elevated in one or more of the whole trailer samples. All pure standards and analytes were referenced to an internal standard (~120 ng) of 1-bromo-4-fluorobenzene.

Low Molecular Weight Aldehydes

The target analytes in the aldehyde analysis included formaldehyde, acetaldehyde and acetone. Higher carbon-number aldehydes were quantified using the VOC method described above. Samples of these low molecular weight carbonyl compounds were collected and analyzed following ASTM Test Method D 5197-92 (ASTM, 1997). As with the VOCs, the air samples were drawn directly from the small emission chamber or through a short rigid tube inserted though holes in the trailer door. Samples were collected on commercially available silica gel cartridges coated with 2,4-dinitrophenyl-hydrazine (XPoSure Aldehyde Sampler; Waters corporation). An ozone scrubber (P/N WAT054420; Waters) was installed upstream of the silica cartridge in the field samples. Samples were collected from the trailers for 60 minutes at ~ 1 lpm using personal sampling pumps that were calibrated before use and checked after use. Samples were collected and times recorded from the emission chambers using a vacuum pump (Model DOA-P104-AA; Gast) with sample flow rates regulated by electronic mass flow controllers. Sample cartridges were capped and stored on blue ice or in the freezer until extraction.

Cartridges were eluted with 2 mL of high-purity acetonitrile into 2 ml volumetric flasks and the eluent was brought to a final volume of 2 ml before analysis. Extracts were analyzed by high-performance liquid chromatography (HPLC) (1200 Series; Agilent Technologies) using a C_{18} reverse phase column with 65:35 H_2O:Acetonitrile mobile phase at 0.35 ml/minute and UV detection at 360 nm. Multipoint calibrations were prepared for the target aldehydes using commercially available hydrazone derivatives of formaldehyde, acetaldehyde and acetone.

Acetic Acid

Acetic acid was collected similarly to the aldehyde samples onto silica gel sorbent tubes (P/N 22655; SKC). Samples were collected from the trailers for 60 minutes at ~ 1 lpm using personal sampling pumps that were calibrated before use and checked after use. Samples were collected and times recorded from the emission chambers using a vacuum pump (Model DOA-P104-AA; Gast) with sample flow rates regulated by electronic mass flow controllers.

Extracts are intended to be extracted using 18 mOhm deionized water and analyzed by ion chromatography (IC) (ICS 2000; Dionex) but instrumentation difficulties have prevented these samples from being analyzed as yet. Acetic acid is detected in the TD-GCMS analysis, although the chromatography is poor. For the preliminary results reported herein, the acetic acid was semi-quantitatively analyzed bases on its total-ion-current response using toluene as the surrogate standard.

Quality Assurance

All samples were quantified with multipoint calibration curves prepared from pure chemicals. For the VOCs that did not have pure standard available or that were a mixture of compounds (i.e., alkylbenzenes), the compounds were tentatively identified by NIST library spectrum search and quantified as toluene equivalent values. Analytical blanks were included in all analyses. Trip blanks were prepared, transported to the field sampling site, stored and analyzed along with the whole trailer samples. Method blanks for the full emission experiments including backing plate and tape in the chamber represented more than 10% of all samples collected and chamber blanks representing only the background in the chamber represented an additional 10% of samples collected.

Measurement of Whole Trailer Concentrations

Air concentrations were measured under pseudo steady-state conditions on November 14, 2007 after the THUs had been closed for several days. No attempt was made to control the ambient wind or temperature that the THUs were subjected to during this period. All THUs were setup with samplers and pumps so that all three samples (VOC, aldehyde and acetic acid) could be collected simultaneously in all THUs. A morning sampling event and an afternoon sampling event were conducted for each trailer and at a central outdoor location. The first sample collection started between 11:00 and 11:30 and continued for approximately one hour during which time the ambient temperature, relative humidity and wind speed were 25.1 ± 2.6% (C) and 49 ± 6.5% (%) and 2.8 ± 41% (m/s), respectively. The second sampling event started between 14:00 and 14:30 and again lasted about an hour during which time the ambient temperature, relative humidity and wind speed were 26.4 ± 1.5% (C), 48 ± 3.2% (%) and 2.6 ± 43% (m/s), respectively. Start and stop times were recorded for each sample along with flow rates. Each sample pump was checked against a calibrated flow meter before and after the sampling event. All samples including two trip blanks for each sample type were sealed and placed on ice for transport back to LBNL. Upon arrival at LBNL the samples were stored in a freezer until analysis.

Measurement of Steady-State Ventilation Rates

The THUs did not include mechanical forced air ventilation systems and operable windows remained closed throughout the study period. Ventilation rates were determined after collection of air samples using a tracer gas decay method. Externally controlled circulation fans were switched on in each trailer and pure carbon dioxide (CO_2) was injected from a Tedlar bag into each unit to achieve an initial concentration that was significantly elevated over ambient conditions. The concentration of CO_2 was measured continuously using Q-Trac IAQ monitors through the sample ports in the trailer doors. Mixing fans were run for 15 - 20 minutes after dumping CO_2 into trailers allowing the air concentrations and decay curves to stabilize then the fans were shut off to while ventilation rates were measured.

The ventilation rate is determined from the decay of the tracer gas concentration in the trailer. When using a chemical like CO_2 as a tracer gas, the background level can influence the clearance rates. The equation for decay or clearance of the tracer gas from a unit after the initial concentration had been artificially elevated and after the initial elevated concentration stabilizes is

$$C_t = C_{ss} + \left(C^* - C_{ss}\right) \times \exp^{-Q\left(t-t^*\right)} \qquad (1)$$

where C_t (ppm) is the measured concentration in the unit at time t, C* is the maximum at the start of the stable decay period, Css is the background or ambient concentration, and Q (h^{-1}) is the rate of removal of the tracer from the system, which for a non-reactive chemical that does not significantly interact with surfaces, is the ventilation rate in terms of air changes per hour, ACH (h^{-1}). Equation 1 can be rearranged to the form

$$\ln\left(C_t - C_{ss}\right) = -Q\left(t - t^*\right) \qquad (2)$$

so the slope of the natural log of the difference between measured concentration and the ambient concentration against elapsed time is the $-ACH$ as illustrated in Figure 3.

Collection and Characterization of Indoor Materials

The total projected surface area in the trailer for each surface material was measured and recorded in the field when the material samples were collected for testing. A representative piece (> 15 cm on a side) of each material was cut directly from the trailer, triple wrapped in foil, placed in a labeled manila envelope and boxed for shipment to LBNL. A total of 45 samples representing 16 different materials were collected from the four trailers. The materials were inventoried upon arrival at LBNL and stored at room temperature in their original packing. Prior to testing, the materials (excluding the fabric and cushions) were cut to size using a dry table saw with sharp blade and returned to their original packing. The fabric and cushion materials were cut to size with a razor or knife. Each material was either pressed into a stainless steel tray to expose only the face or the back was covered with a stainless steel plate and the edges sealed with aluminum tape. When tape was used to seal the edges, the final exposed face was measured and recorded. The individual material samples had already aged in the trailers prior to collection of the test materials so we did not include an additional conditioning period prior to testing.

Measurement of Material Specific Emission Factors

Material specific emission factors were determined using small chambers generally following the ASTM Standard Guide D-5116-97. Because the goal was to reconstruct whole-trailer emission rates and the trailers were well aged in the field, the individual materials were not conditioned prior to testing. Also, the air-sampling period in the small chambers started after approximately six air changes rather than the recommended 96 hour pre-test period used for new materials. This approach was taken to provide emission factors that were more closely linked to the actual emission rates measured in the whole trailers.

The emission tests were conducted in 10.5 liter stainless steel chambers that were maintained at 23 ± 1 ^{o}C in an environmental chamber with a 0.06 m^3/h inlet flow of carbon filtered preconditioned air at 50% ± 5% relative humidity supplied continuously to each chamber. The relative humidity within the chamber was controlled by a flow of mixed streams of dry- and water-saturated air. After sealing the backs and raw edges of the material as described above, the materials were placed face up on screens resting slightly below the center of the test chambers. The emitting area, A, (m^2) was 0.023, the loading factor, L, (m^2/m^3) was 2.2 and the area specific flow rate ($m^3/m^2/h$) was typically 2.6. The collection of air samples was initiated after at least six air changes and the VOC, aldehyde and acetic acid samples were all collected from the chamber exhaust stream at a total rate less than 90% of the inlet air stream.

Data Analysis

The whole trailer emission rates normalized to floor area and the material specific emission factors normalized to projected surface area were calculated assuming that the systems were at pseudo steady-state and were well mixed. The steady-state form of the mass balance equation for calculating area-specific emission rates, ER, ($\mu g/m^2/h$) in a well-mixed system is

$$ER = \frac{f \times (C - C_0)}{A} \tag{3}$$

where f (m^3/h) is the ventilation flow rate, A (m^2) is the exposed surface area of the material or the floor area of the whole trailer, C (μg/m^3) is the measured steady state concentration in the chamber or trailer and C_0 (μg/m^3) is the background concentration in the chamber or the outdoor concentration for the whole trailer experiments. Ventilation rate in terms of air flow are not readily available for the whole trailer measurements but given that ACH is equal to the ventilation rate divided by the volume (f/V) and the loading factor is equal to the exposed area divided by the volume, Eq. 3 can be rearranged to give

$$ER = \frac{ACH \times (C - C_0)}{L} \tag{4}$$

where L (m^2/m^3) is the loading factor in the chamber. To relate the material specific emission factors to the whole trailer emission rates we multiply the material specific emission rates by the projected surface area of the material and divide by the floor area of the THU. Normalizing to floor area facilitates comparison among units of different size. To get the floor area normalized emission rate for the whole trailer experiments we note that ACH is equal to f/V as indicated above and that V is the floor area multiplied by the height, h (m) so that Eq. 2 may also be written as

$$ER = ACH \times h \times (C - C_0). \tag{5}$$

The formaldehyde emission rates were compared across trailers and differences between the morning samples and afternoon samples were tested in Excel using the TTest function with two tailed distribution and assuming the samples were of unequal variance. A probability associated with a Student's paired t-Test with a two-tailed distribution less than 0.05 is considered significant.

RESULTS

Material specific loading ratios

The loading ratio for the different composite wood categories in the THUs are compared to the recommended loading ratios in the HUD standard and the ASTM E6007 Standard in Table 5. The loading ratios are calculated from the total amount of each composite wood type found in each THU and the approximate internal volume of the THU where volume includes the entire indoor space. No attempt was made to determine readily exchangeable volume so the actual loading ratio may be greater than reported in Table 5. Additionally the ratio of air flow (f) to projected surface area of each wood type in each THU is calculated and compared to the values defined in the HUD standard (Section 408). The air flow is estimated as the product of the internal volume and air exchange rate. Again, no attempt was made to determine readily exchangeable internal volume so the f/A values reported in Table 5 might be biased high, i.e., actual flows are likely to be lower than what is calculated in Table 5. These calculations show that the loading ratios for Hardwood plywood range from between 2 to 3 times the loading ratio used in the HUD standard for which the concentration limits are established. The f/A ratios in the THUs do not match the ratios those used in the standard. Using HUD compliant HWPW at the loading ratio found in the four different manufactured THUs would be expected to deliver a room concentration 2 to 3 times the HUD concentration limit with all other things being equal.

Whole trailer Ventilation and VOC measurements

When determining ventilation rates, the linear region of the decay curves in the tracer experiment were monitored for approximately 2 hours after the CO_2 had stabilized in each THU. The duration of the decay curves and the correlation coefficient (r^2) from the calculation of ACH are included in Table 1. The outdoor CO_2 concentration during the ventilation measurements was 366 ppm ± 1.6% and the indoor starting concentration for the decay curves were a factor of 9.3, 6.5, 6.8 and 6.6 greater than outdoors for the Dutchmen, Pilgrim, Coachmen and Cavalier, respectively. The minimum tracer concentration indoors relative to outdoor levels at the end of the CO_2 decay period was greater than a factor of 3.4 for all units. The temperature, relative humidity and wind speed (average ± the percent coefficient of variation (CV)) measured during the two VOC sampling periods and during the tracer gas experiment are summarized in Table 6. Wind speed and indoor/outdoor temperature gradient were similar for the AM and PM air sampling events. The tracer gas-sampling period had calm wind conditions and the indoor/outdoor temperature gradient was elevated compared to the air sampling times.

In the initial qualitative analysis of VOC samples from the four THUs, approximately 80 individual compounds were tentatively identified. Forty-five of the compounds were positively identified and quantified. These target compounds were selected because they were toxicologically important (i.e., benzene) and/or their concentrations were relatively high. Thirty-three of the 45 chemicals that were quantified had steady-state concentrations above 0.4 $\mu g/m^3$ in one or more of the units. The 33 VOCs are listed in Table 7 sorted by chemical class and increasing boiling point.

A number of higher molecular weight alkyl-benzenes were detected in one THU. These alkyl-benzenes had analytical retention times between 36 and 40 minutes in the GC analysis and were combined and quantified as toluene equivalents. The 2,2,4-Trimethyl-1,3-pentanediol diisobutyrate (TMPD-DIB, TXIB) was quantified as 2,2,4-Trimethyl-1,3-pentanediol monisobutyrate (TMPD-MIB, Texanol) although the toluene equivalent quantification gave similar results. The steady-state concentration for each compound in the morning and afternoon samples is given in Table 8 along with the AM and PM outdoor concentrations. The indoor concentrations are converted to whole trailer indoor emission rates normalized to the floor area for each unit and presented in Table 9.

Material Specific VOC measurements

All THUs had a significant fraction of the internal surface area (walls, ceiling, cabinet walls) constructed of 1/8-inch plywood with a vinyl or PVC skin or simulated wood finish. All units had sheet vinyl flooring while the Dutchmen and Pilgrim also had carpeted areas. All countertops were particleboard surfaced with high-pressure laminate. A variety of wood products were used for the sub-floor and for the bench and bed platforms.

Material specific emission factors were measured for the same target chemicals that were included in the whole trailer measurements. The emission factors for each material are first summarized by THU in Table 10 through Table 13. These values are converted to whole trailer emission factors for each THU by multiplying the measured emission factor by the projected surface area for that material in the trailer then dividing by the total floor area of the trailer. These results are presented in Table 14 through Table 17.

The values in Table 14 through Table 17 are transformed to the approximate percent contribution to total pollutant load in each THU and the material-chemical combinations that represent greater than 5% are reported in Table 18 through Table 21. As an example, the total emissions of formaldehyde from all materials in the Pilgrim reported in Table 19 is 478 ($\mu g\ m^{-2}\ h^{-1}$) and 56% of that is from "cabinet" material with small fractions from the bed deck (5%), curtain (6%), seat cushion (8%) and the walls (14%). These percentages should be treated as approximations given the limited number of samples tested and the differences between the test conditions and the actual whole trailer conditions. In addition, the results cannot distinguish from primary sources and secondary sources that are re-emitting materials that have been sorbed over time in the THU.

The total material specific emission factors across all materials normalized to the THU floor area are compared to the average of the two field measurements for the whole trailer emission factors for each THU in Table 22. These results further illustrate that the dynamics in the whole THU likely suppress emissions from the primary sources given the long-term mixing of pollutants among the indoor sources and competitive emissions in the whole trailer that do not exist in the small chamber experiments with individual materials.

DISCUSSION

Building material emission measurements for formaldehyde and other VOCs have been published in the literature over recent years. These emission factors may be used for comparison to those measured in the THUs. However, it is important to note that both the whole THU emission rates and the material specific measurements represent materials that have been exposed to the entire mixture of VOCs in the indoor environment for the life of the THU. The values do not necessarily reflect primary emissions as are measured typically in standard protocols where new, unexposed materials are tested after a specific aging process. Nevertheless, we can tentatively identify likely sources of the VOCs in the THUs based on other studies in combination with the material-specific measurements from this study.

Volatile Organic Compound (VOC) Emissions from Building Materials

Hodgson et. al. (2000) measured VOC concentrations under pseudo-steady state conditions in four new manufactured homes and seven site-built houses. The geometric mean concentrations (ppb) are reported for each housing type. Hipelein (2004) measured indoor air VOC concentrations in 79 rooms in 39 private dwellings in Germany. The homes were not associated with health complaints but 27% of the rooms investigated were occupied by smokers. No information is provided about the ages of the dwellings. Geometric mean concentrations (ug/m^3) were reported for a number of VOCs. These values are transformed to units of ppb using conversion factors reported by Hodgson and Levin (2003). The reported indoor concentrations from each of the studies are compared to the four THUs from this project for both the AM sampling period and the PM sampling period in Figure 4. Results from the Hipelein (2004) study are consistently lower than the values reported for the new dwellings by Hodgson et. al. (2000). Although many of the VOCs measured in the THUs are similar to reported residential values, several are in excess. Dodecane, tridecane, p-xylene, alpha-pinene, beta-pinene and hexanal are all above values reported in the German homes while phenol, TMPD-DIB and formaldehyde are even in excess of values measured in the new dwellings.

In addition to reporting indoor concentrations of VOCs, Hodgson et.al., (2000) also report whole unit emission rates normalized to floor area. Figure 5 compares these VOC emission factors measured in the four THUs with the whole building emission factors for new site-built and manufactured houses. The compounds presented in the figure were selected from the available data because they were included in the THUs studied in this report. These compounds represent a wide range of functional groups including terpenes, alcohols, ester alcohols, aldehydes, and organic acids. The median whole building emission factors in the THUs were lower than from the newly constructed dwellings for twelve of the eighteen compounds compared. All of the alkane and terpene compound emissions were lower in the THUs than in the new houses, as were TMPD-MIB, acetic acid, and the aldehydes, *excluding* formaldehyde. The lower emission factors in the THUs may be due to aging where the four THUs tested were more than 1 ½ years old while the site-built and manufactured homes were all approximately 6 months old or less. In contrast, the emission factors for phenol, TMPD-DIB, and formaldehyde remained higher in the THUs than the new homes.

These results provide a general focus for discussion of the VOC and aldehyde emissions within the THUs studied. The measured emissions of the ester alcohol TMPD-DIB are large, likely due to the relatively large amounts of vinyl flooring and other vinyl materials in the THUs. The fact that the levels summed across all materials exceeded that which was measured in the whole THUs for a number of the chemicals is likely an indication of suppression of emissions from the individual materials in the THUs. This can occur where some of the surfaces act as sinks and secondary re-emission sources that compete with the primary emission source of any individual chemical and material. Interestingly the Coachmen had far lower whole trailer TMPD-DIB emissions than the other three units; possibly due to the far lower emissions of the compound from the vinyl floor in that THU. Elevated levels of the high molecular weight alkyl-benzenes in that THU indicates the use of these chemicals as the plasticizers in place of TMPD-DIB in some vinyl flooring.

Measurements of Aldehyde Emissions from Wood Products

Hodgson et al. (2002) measured material specific emissions of aldehydes and terpenes for a single new manufactured house. The study selected materials from a newly constructed modular home and collected the materials direct from the factory that fabricated the dwelling. The new materials were tested in small emission chamber to determine material specific emission factors. Indoor house measurements were also collected in the newly manufactured home and the material emission factors were used to reconstruct whole house emission rates. Table 23 and Table 24 present the aldehyde and terpene emissions, respectively, from material samples. This study, along with an earlier report (Hodgson, 1999) identified composite woods made with urea-formaldehyde resin as important formaldehyde and terpene hydrocarbon sources in buildings.

The State of California has conducted studies and has initiated various programs and regulations intended to lower material emissions of formaldehyde since the California Air Resource Board (CARB) identified the compound as a Toxic Air Contaminant (TAC) in 1992 (CalEPA, 1992).

Part of this effort included a survey of emissions from composite wood products on the market in California, conducted by Battelle Labs during 1995 (Battelle 1996; Kelly et al. 1999). The results were summarized by CARB (CARB 2008) and are reproduced in Table 25.

Measured formaldehyde concentrations in the unoccupied THUs ranged from 378 $\mu g\ m^{-3}$ (0.31ppm) to 632 $\mu g\ m^{-3}$ (0.52 ppm) in the AM samples, and from 433 $\mu g\ m^{-3}$ (0.35 ppm) to 926 $\mu g\ m^{-3}$ (0.78 ppm) in the PM samples. When the THUs are occupied, differences in ventilation rates, temperatures, relative humidity and indoor air movement may influence the steady-state concentration of VOCs but information is currently lacking on the magnitude and direction of this influence.

Whole THU formaldehyde emissions (per floor area) measured at Purvis ranged from 173 to 266 $\mu g\ m^{-2}\ h^{-1}$ in the AM and 257 to 347 $\mu g\ m^{-2}\ h^{-1}$ in the PM. Median formaldehyde emissions in previously studied site-built and manufactured homes were 31 and 45 $\mu g\ m^{-2}\ h^{-1}$, respectively (Figure 5 and Hodgson 2000). The material specific formaldehyde emission factor measurements (Table 10-Table 13) showed that the highest material emissions were from the cabinet walls, sub flooring, and the bench materials (the fabric and foam materials also showed elevated emissions, but these are likely due to the re-emission of formaldehyde that had sorbed to the material from the indoor air, rather than as primary emitters). Only one material, the Cavalier plywood cabinet wall (490 $\mu g\ m^{-2}\ h^{-1}$) exhibited emissions in excess of the HUD standard of 130 $\mu g\ m^{-2}\ h^{-1}$ (for calculation of the HUD based emission rates see footnote on page 3 of this document). Formaldehyde emission factors from the various composite wood materials appear to be well within the range found in previously published research (Table 23- Table 25) although significant differences can be expected due to the aging of the material in the THUs. Therefore it is difficult to conclude that the material would have been within previously reported range had the tests been conducted using fresh materials.

Thus, whole trailer formaldehyde emissions factors are high, but the materials emission factors may be within those commonly found in the building industry. This indicates a difference in the construction/design that may lead to elevated concentrations and whole trailer emission rates. Three features of material application in the THUs differ from most other dwellings: 1) the extensive use of lightweight composite wood products, 2) very high surface loading of composite wood products and 3) low fresh air per unit surface area of composite wood products in the THUs. Much of the projected surface area in the THUs (wall, ceiling, and cabinetry) use 1/8" plywood. These materials are used presumably to reduce weight relative to the gypsum board material used in conventional houses. Almost all surfaces in these structures are wood. The wood product loading factor of the THU is far higher than in housing that uses gypsum for walls and ceilings. The combination of these factors is likely to be the cause of the unusually high rates at which formaldehyde mass is emitted into the THU. Considering this in terms of the area-specific clean air flow rates, the high material loading ratio in the units combined with relatively low fresh air ventilation rates results in area-specific air flow rates that are quite low relative to other housing types. With all other factors being equal, the steady-state concentrations indoors are inversely proportional to the air exchange rates as indicated in Eq. 4. The THUs in this study are not outfitted for adequate ventilation and are tighter than would be desired for housing with such small volume. Although low ventilation does not directly affect the measured formaldehyde emission rates presented in this report, it can influence the concentrations experienced by occupants, the issue of greatest concern.

CONCLUSIONS

A large number of THUs are owned by the Federal Emergency Management Administration. Although it may not be scientifically defensible to develop a judgment regarding the entire fleet of THUs based on the measurements of the convenience sample of four units presented in this study, the measured material-specific emission factors for volatile organic compounds, including formaldehyde, were not atypical relative to the literature for materials. However, it is important to consider that the materials in this study were both aged and allowed to interact with emissions from other materials. Formaldehyde and some of the other VOCs measured in the unoccupied THUs and the associated whole trailer emission factors were found to be higher, sometimes much higher, than what is typically found in residential environments. The difference between these THUs and other housing appears to be the very high composite wood surface area relative to room volume used in the travel trailer design and the low ventilation rates in terms of low area-specific fresh air flow rates in the THUs.

Recommendations for future work

This interim report provides a preliminary assessment into the effect of THU design and material choices on indoor VOC and aldehyde concentrations. It is by no means definitive as a convenience sample of only four THU models produced by four manufactures was evaluated. Additionally, the focus of this study was on the travel trailers, while a significant portion of THUs are park trailer models, and mobile homes. A systematic assessment across a wider range of THU makes and models including a better characterization of fresh air ventilation rates under occupied conditions could provide a better understanding of the time integrated exposure concentrations in occupied units.

The results in this report do not yet address temperature and humidity effects on material emissions within the studied units. It is hypothesized that at the higher temperature and relative humidity conditions found in the summertime in the southeastern portions of the US, emissions of formaldehyde from the urea-formaldehyde composite woods will increase. Chamber experiments and a seasonal study designed to investigate the potential effects of temperature and humidity should be completed.

Recommendations for formaldehyde mitigation approaches for the THUs have not been provided. An assessment of the literature for information on the effectiveness of material coverings should be considered. As part of this effort to explore the influence of diffusion resistance at the material surface, the resistance to diffusion on the air-side of surfaces as influenced by airflow and boundary layer effects should be considered. As part of this effort, it would be informative to explore the effect of material aging and the role of different material types as surface sinks and sources of secondary emissions of indoor pollutants and how this impacts the primary emission source material.

ACKNOWLEDGEMENTS

This work was supported by interagency agreement 08FED894632 from CDC – NCEH and also the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of CDC –NCEH or US DOE. We would like to thank Mike Gressel and Chad Dowell of CDC-NIOSH for their technical and field support on this project. We would also like to thank Al Hodgson and Toni Stein for their detailed and thorough reviews of this report.

REFERENCES

ATSDR. 1999. Toxicological profile for Formaldehyde. Agency for Toxic Substances and Disease Registry, Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

ASTM (2002), Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber, ASTM Test Method E 1333-96.

Azuma K., Uchiyama I. Ikeda K. 2006. "The risk management for indoor air pollution caused by formaldehyde in housing: The historical perspectives on early warnings and actions," *Facilities,* Vol. 24 No. 11/12, pp. 420-429.

Battelle. 1996. Determination of Formaldehyde and Toluene Diisocyanate Emissions from Indoor Residential Sources. Final Report, CARB Contract No. 93-315, Research Division, Sacramento, CA.

CARB. 2008. Rulemaking to Consider Adoption of the Proposed Airborne Toxic Control Measure (ACTM) to Reduce Formaldehyde Emissions From Composite Wood Products, California Air Resources Board. April 2007. http://www.arb.ca.gov/regact/2007/compwood07/compwood07.htm

CalEPA. 1992. *Final Report on The Identification of Formaldehyde as A Toxic Air Contaminant*. Prepared by the California Air Resources Board and the Office of Environmental Health Hazard Assessment, Sacramento CA. http://www.oehha.org/air/toxic_contaminants/html/Formaldehyde.htm

CIWMB. 2003. *Building Materials Emissions Study*. Integrated Waste Management Board. Public Affairs Office, Publications Clearinghouse, Sacramento CA. http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc46265/ www.ciwmb.ca.gov/Publications/

CPSC. 1982. *CPSC Bans Urea Formaldehyde Foam Insulation (UFFI)*, Consumer Product Safety Commission NEWS from CPSC, Release No. 82-005, March.

CPSC. 1983. *Ban on UFFI Lifted.* Consumer Product Safety Commission, NEWS from CPSC, Release No. 83-048.

Hileman, B. 1982. "Formaldehyde. How did EPA develop its formaldehyde policy?", *Environmental Science & Technology*, Vol. 16 No.19, pp.543A-7A.

Hipeleim, M. (2004) "Background concentrations of individual and total volatile organic compounds in residential indoor air of Schleswig-Holstein, Germany" J. Environ. Monit. Vol. 6, 745-752.

Hodgson, A.T. (1999) *Common Indoor Sources of Volatile Organic Compounds: Emission Rates and Techniques for Reducing Consumer Exposures*, Final Report, Contract No. 95–302, Sacramento, CA, California Air Resources Board.

Hodgson, A.T., Rudd, A.F., Beal, D. and Chandra, S. (2000) "Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses", *Indoor Air*, **10**, 178-192

Hodgson, A.T. and H. Levin (2003) "Volatile Organic Compounds in Indoor Air: A Review of Concentrations Measured in North America Since 1990" Report LBNL-51715.

Hodgson, A.T., Shendell, D.G., Fisk, W.J. and Apte, M.G. (2004) "Comparison of predicted and derived measures of volatile organic compounds inside four new relocatable classrooms", *Indoor Air*, **14**, 135-144.

HUD. 2006. *Manufactured Home Construction And Safety Standards,* --Housing and Urban Development Office of Assistant Secretary For Housing--Federal Housing Commissioner, Department Of Housing And Urban Development, Washington DC. CFR 24 Chapter XX--Parts 3280.308 and 3280.407.

Kelly, T.J., Smith, D.L., and Satola, J. 1999. "Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes", *Environ. Sci. Technol*., 33 (1), 81 -88.

Matthews T.G. 1985. *Modeling and Testing of Formaldehyde Emission Characteristics of Pressed-Wood Products: Report XVIII to the U.S. Consumer Product Safety Commission,* Oak Ridge National Laboratory, Oak Ridge TN. ORNL/TM-9867

NAS. 1980. *Formaldehyde – An Assessment of its Health Effects, Committee on Toxicology*, Board on Toxicology and Environmental Health Hazards, National Research Council, National Academy of Sciences, Washington, DC.

OEHHA. 2008a. *Chronic Toxicity Summary – Phenol*, Office of Environmental Health Hazards Assessment, California Environmental Protection Agency, Sacramento CA. http://www.oehha.org/air/chronic_rels/AllChrels.html

OEHHA. 2008b. *Chronic Toxicity Summary – Formaldehyde*, Office of Environmental Health Hazards Assessment, California Environmental Protection Agency, Sacramento CA. http://www.oehha.org/air/chronic_rels/AllChrels.html

OEHHA. 1999. *Acute Toxicity Summary – Formaldehyde*, Office of Environmental Health Hazards Assessment, California Environmental Protection Agency, Sacramento CA. http://www.oehha.org/air/acute_rels/allAcRELs.html

SEFA. 2008. "Formaldehyde Emissions and Particle Board Core Products," by Dave Withee, formerly of Case Systems Inc., the Scientific Equipment and Furniture Association, Garden City, NY. On the web at: http://www.sefalabs.com/i4a/pages/index.cfm?pageID=3394

Turner S., Martin C., Hetes R., and Northeim C. 1996. *Project Summary - Sources and Factors Affecting Indoor Emissions from Engineered Wood Products: Summary and Evaluation of Current Literature*, United States Environmental Protection Laboratory Agency, National Research Risk Management, Research Triangle Park NC 27711 EPA/600/SR-96/067.

Won, D., R. L. Corsi* and M. Rynes (2001) "Sorptive Interactions between VOCs and Indoor Materials" V 11:4 Page 246-256

Won, D.; Magee, R.J.; Lusztyk, E.; Nong, G.; Zhu, J.P.; Zhang, J.S.; Reardon, J.T.; Shaw, C.Y. (2004) "A Comprehensive VOC emission database for commonly-used building materials", Institute for Research in Construction, National Research Council, Ottawa, Ontario, Canada, Report NRCC-46265. http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc46265/ last visited April 28, 2008.

TABLES

Table 1. Specifications and Ventilation Characteristics of the Temporary Housing Units

	Trailer			
Manufacturer	Thor Industries	International	Spirit of America	Gulfstream
Model	Dutchmen	Pilgrim	Coachmen	Coach Cavalier
VIN	47CTDER256G520549	5L4TF332563013658	1TC2B970861308196	1NL1VTR2661064665
Manufactured	Sep 2005	Oct 2005	Oct 2006	Mar 2006
FEMA Specs.	No	Yes	No	Yes
Floor area (m^2)	20.16	20.34	22.43	19.94
Internal height (m)	2.08	1.98	2.06	1.98
Internal Volume (m^3)	41.9	40.3	46.2	37.9
Ventilation Characteristics				
ACH[a] (h^{-1})	0.25	0.15	0.39	0.21
Duration of linear tracer decay (min)	153	135	142	118
r^2 for linear region of tracer decay	0.998	0.999	0.998	0.998
Apparent Air Flow[b] (m^3/h)	10.5	6.0	18.0	8.0

[a] ACH, air changes per hour measured after the final sampling event of the day. [b] Apparent Air Flow is the product of internal volume and ACH and represents the fresh air flow through the THU

Table 2. Projected Surface Area of Indoor Materials (m^2)

	Trailer			
Material	**Dutchmen**	**Pilgrim**	**Coachmen**	**Cavalier**
Ceiling	**23.61**	**19.44**	**24.05**	**18.99**
Walls	**60.13**[a]	**40.70**	**63.12**	**60.52**
Subfloor	**23.61**	**20.34**	**22.43**	**19.94**
Carpet	**8.29**	**7.36**		
Vinyl floor	**17.70**	**12.98**	**22.43**	**19.94**
Cabinet Walls	**30.00**	**13.17**	**6.87**	**17.80**
Cabinet Ends	**2.64**		**0.91**	**0.16**
Countertop	**2.72**	**1.56**	**1.79**	**1.14**
Interior Door	**2.79**	**2.04**	**0.98**	**1.86**
Exterior Door	1.02	1.02	1.02	1.02
Trim board	**1.18**			
Fabric	7.18	6.84	6.58	7.04
Fabric Divider			**3.40**	
Bed Platform MDF	**6.09**			**6.78**
Bed Platform Plywood			**5.42**	
Bed Platform OSB		**3.89**	**2.70**	
Tub surround	3.20	3.24	3.20	3.74
Windows	5.44	**1.76**[b]	2.55	1.76
Vinyl seat[c]	**2.50**	**2.01**	**1.96**	**2.06**

[a] numbers written in bold text indicate that the material was included in set for determination of emission factors ; [b] window area used to represent fabric curtain material; [c] vinyl seat areas used to represent projected surface area of seat/cushion material

Table 3. Description of Surface Materials Harvested from Trailers and Tested for Emissions

	Trailer			
	Dutchmen	**Pilgrim**	**Coachmen**	**Cavalier**
ceiling	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood
wall	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood
sub floor	5/8 inch plywood	5/8 inch plywood	9/16 inch OSB[a]	5/8 particle board/OSB finer fiber and darker resin
carpet	Low pile with backing	Low pile with backing		
vinyl floor	vinyl with slight residue of glue on back	vinyl does not have indication of glue	vinyl does not have indication of glue	vinyl does not have indication of glue
cabinet wall	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood	1/8 inch plywood
cabinet wall thick	½ inch HB[b] or MDF[d]			
cabinet door				½ inch HB or MDF
countertop	5/8 inch PB[c]	5/8 inch PB	½ inch PB	5/8 inch PB
door	Hollow core 1/8 inch HB panels (1 smooth back, 1 textured back) with cardboard fill	Hollow core 1/8 inch HB panels (both textured back) with cardboard fill	Hollow core 1/8 inch HB panels (both smooth back) with cardboard fill	Hollow core 1/8 inch HB panels (1 smooth back, 1 textured back) with cardboard fill
trim	3/8 inch MDF			
curtain/door fabric			fabric	plastic impregnated fabric
seat cushion	fiber fill material (white) with fabric cover	Polyurethane foam dense and light in color covered with 2 layers plastic film and fabric	Polyurethane foam dense and light in color covered with simulated fiber, 2 layers plastic film and fabric	fiber fill material (white) with fabric cover
seat bottom/bed platform	3/8 inch PB	3/8 inch OSB	1/2 inch OSB	3/8 inch MDF
bench-seat bunk bed platform			3/8 inch plywood	
bench end			1/2 inch MDF	

[a] OSB, oriented strand board; [b] HB, hardboard or high density fiber board; [c] PB, particle board; [d] MDF, medium density fiber board

Table 4. Surface Coverings and Finishes on Tested Materials

Material	Trailer			
	Dutchmen	Pilgrim	Coachmen	Cavalier
ceiling	textured white pvc or vinyl finish with unfinished veneer backing	textured white pvc or vinyl finish with unfinished veneer backing	textured white pvc or vinyl finish with unfinished veneer backing	textured white pvc or vinyl finish with unfinished veneer backing
wall	pvc or vinyl laminant with unfinished veneer backing	pvc or vinyl laminant with unfinished veneer backing	pvc or vinyl laminant with unfinished veneer backing	pvc or vinyl laminant with unfinished veneer backing
sub floor	unfinished	unfinished	unfinished	unfinished
carpet	Low pile	low pile		
vinyl floor	vinyl	vinyl	vinyl	vinyl
cabinet wall	simulated wood photo laminate front with veneer backing	simulated wood photo laminate front with veneer backing	simulated wood photo laminate front with veneer backing	simulated wood photo laminate front with veneer backing
cabinet wall thick	simulated wood photo laminate finish both sides			
cabinet door				simulated wood photo laminate finish both sides
countertop	HP Laminate with backing covered with a slightly thicker layer of Formica	HP Laminate with backing cover of dense brown paper.	HP Laminate with backing cover of dense brown paper.	HP Laminate with backing cover of dense brown paper.
door	Simulated wood photo laminate each side (oak & maple)	Simulated wood photo laminate (maple)	Simulated wood photo laminate (oak)	Simulated wood photo laminate each side (oak & maple)
trim	simulated wood photo laminate front and sides, back unfinished			
curtain/door fabric		loose weave polyester fabric	loose weave fabric pleated and impregnated with plastic	
seat cushion	fabric with vinyl material for back (vinyl not tested)	Fabric with vinyl material for back (vinyl not tested)	Fabric with vinyl material for back (vinyl not tested)	fabric with vinyl material for back (vinyl not tested)
seat bottom/bed platform	simulated wood photo laminant on one surface and unfinished on back	unfinished	unfinished	unfinished
bench-seat bunk bed platform			unfinished veneer both sides	
bench end			simulated wood photo laminate	

Table 5. Surface Loading Ratios and Area-Specific Clean Air Flow Rates

Hardwood Plywood (HWPW)	**Dutchmen**	**Pilgrim**	**Coachmen**	**Coach Cavalier**
HWPW Surface Area (m^2)	137	94	99	97
HWPW Loading Ratio (m^2/m^3)	3.28	2.33	2.15	2.46
ASTM E1333 Loading Ratio (m^2/m^3)	0.95	0.95	0.95	0.95
HWPW flow/area (m/h)	1.22	2.87	1.19	1.93
ASTM E1333 flow/area (m/h)	0.53	0.53	0.53	0.53
Particleboard (PB)				
PB Surface Area (m^2)	5	2	2	21
PB Loading Ratio (m^2/m^3)	0.12	0.04	0.04	0.53
ASTM E1333 Loading Ratio (m^2/m^3)	0.43	0.43	0.43	0.43
PB flow/area (m/h)	32	172	66	9
ASTM E1333 PB flow/area (m/h)	1.17	1.17	1.17	1.17
Medium Density Fiberboard (MDF) and Hardboard (HB)				
MDF,HB surface Area (m^2)	10	0	2	9
MDF, HB Loading Ratio (m^2/m^3)	0.24	0.00	0.04	0.23
ASTM E1333 Loading Ratio (m^2/m^3)	0.26	0.26	0.26	0.26
MDF flow/area (m/h)	17	0	60	21
ASTM E1333 MDF flow/area (m/h)	1.91	1.91	1.91	1.91
Particleboard Door Core				
Door Core Surface Area (m^2)	4	3	2	3
Door Core Loading Ratio (m^2/m^3)	0.09	0.08	0.04	0.07
ASTM 6007 Loading Ratio (m^2/m^3)	0.13	0.13	0.13	0.13
Door Core flow/area (m/h)	44.02	87.74	59.24	65.28
ASTM 6007 flow/area Ratio (m/h)	3.85	3.85	3.85	3.85

Table 6. Environmental Conditions

	Temperature (C)	RH	Wind speed (m/s)
AM sample period (11:05 – 12:23)			
Dutchmen	24.3 ± 1.1%	55 ± 1.2%	
Pilgrim	22.8 ± 1.1%	55 ± 2.9%	
Coachmen	25.1 ± 1.0%	55 ± 1.6%	
Cavalier	21.9 ± 1.1%	58 ± 2.1%	
Outdoors	25.1 ± 2.6%	49 ± 6.5%	2.8 ± 41%
PM sample period (14:00 – 15:20)			
Dutchmen	28.4 ± 1.0%	48 ± 4.4%	
Pilgrim	27.2 ± 1.6%	46 ± 7.9%	
Coachmen	29.6 ± 2.6%	46 ± 8.9%	
Cavalier	25.7 ± 1.9%	49 ± 10%	
Outdoors	26.4 ± 1.5%	48 ± 3.2%	2.6 ± 43%
Tracer gas sample period (16:00 – 19:00)			
Dutchmen	26.8 ± 2.3%	55 ± 3.6%	
Pilgrim	25.6 ± 2.9%	55 ± 4.7%	
Coachmen	26.1 ± 2.6%	59 ± 3.8%	
Cavalier	25.0 ± 2.7%	66 ± 3.9%	
Outdoors	21.6 ± 4.2%	80 ± 10%	0.8 ± 50%

Table 7 Target VOCs Identified in Temporary Housing Units

Target Compound	CAS#	Chemical Class	BP (C)
Acetic acid[a]	64-19-7	Acid	118
Phenol	108-95-2	Alc	182
1-Hexanol, 2-ethyl-	104-76-7	Alc	183
Formaldehyde[b]	50-00-0	Ald	-19
Acetaldehyde[b]	75-07-0	Ald	20
Hexanal	66-25-1	Ald	128
Octanal	124-13-0	Ald	174
Benzaldehyde	100-52-7	Ald	179
Nonanal	124-19-6	Ald	195
Dodecane	112-40-3	Alka	216
Tridecane	629-50-5	Alka	236
Tetradecane	629-59-4	Alka	252
Pentadecane	629-62-9	Alka	270
Hexadecane	544-76-3	Alka	287
Benzene	71-43-2	Arom	80
Toluene	108-88-3	Arom	111
Ethylbenzene	100-41-4	Arom	136
p-Xylene	106-42-3	Arom	139
Styrene	100-42-5	Arom	145
Benzene, propyl-	103-65-1	Arom	159
Benzene, 1,3,5-trimethyl-	108-67-8	Arom	165
Benzene, 1,2,3-trimethyl-	526-73-8	Arom	175
AlkylBenzenes (36 min - 40 min)[c]		Arom	
TMPD-MIB[d]	25265-77-4	Estr	244
TMPD-DIB	6846-50-0	Estr	280
Acetophenone	98-86-2	Ket	202
Cyclotrisiloxane, hexamethyl-	541-05-9	Misc	134
Cyclotetrasiloxane, octamethyl-	541-02-6	Misc	175
Dimethyl methylphosphonate	756-79-6	OP	181
1R-.alpha.-Pinene	7785-70-8	Terp	155
3-Carene	13466-78-9	Terp	165
beta.-Pinene	18172-67-3	Terp	166
D-Limonene	5989-27-5	Terp	177

[a] acetic acid quantified as toluene equivalents; [b] low molecular weight aldehydes were analyzed by HPLC; [c] the series of alkyl-benzenes eluting between 36 and 40 minutes are combined and quantified as toluene equivalents; [d] TMPD-DIB was quantified as TMPD-MIB (Texanol)

Table 8. Measured Steady-state VOC Concentrations (μg/m^3) in Field Samples

			Trailers							
	Outdoors		Duchmen		Pilgrim		Coachmen		Cavalier	
Target Compound	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**
Acetic acid			69.17	104.73	89.62	152.73	10.35	22.86	88.82	121.31
Phenol	5.76	4.29	24.46	36.14	40.20	58.63	18.31	23.66	31.82	49.67
1-Hexanol, 2-ethyl-	0.91	0.30	1.38	2.70	2.00	4.08		0.49	4.77	7.85
Formaldehyde	2.06	3.34	378.09	486.59	601.52	926.01	330.94	433.36	631.53	763.86
Acetaldehyde	2.03	2.32	12.07	12.55	13.25	15.25	7.18	6.16	10.06	9.28
Hexanal		0.23	12.47	18.35	22.70	31.27	7.42	7.79	34.79	44.31
Octanal	0.29	0.40	4.93	7.51	5.22	7.67	1.97	2.63	6.39	8.79
Benzaldehyde	5.79	4.30	1.62	2.80		1.39			1.52	3.70
Nonanal	0.37	0.52	6.97	12.40	9.86	11.88	5.23	6.84	9.48	16.11
Dodecane	0.04		0.27	0.42	11.18	15.09	0.33		1.26	1.89
Tridecane	0.10	0.04	11.27	23.71	132.28	177.63		1.24	40.69	60.83
Tetradecane	0.38	0.25	25.68	37.76	95.23	124.81	30.89	41.10	38.19	56.87
Pentadecane	0.31	0.20	5.99	9.49	8.35	12.12	20.37	27.04	5.56	9.26
Hexadecane			1.50	2.29	1.97	3.38	4.40	6.11	1.82	3.08
Benzene	0.68	0.64			0.13					
Toluene	0.16	0.20	2.79	1.57	1.23	1.04	1.15	0.50	1.46	1.33
Ethylbenzene		0.06	0.37	0.20	0.43	0.37	0.31	0.15	0.61	0.60
p-Xylene		0.07	0.40	0.29	0.44	0.37	0.43	0.23	0.35	0.28
Styrene	0.02	0.01	9.16	4.15	14.37	11.20	4.52	1.56	20.08	17.18
Benzene, propyl-							0.56			
Benzene, 1,3,5-trimethyl-			0.09	0.13	0.45	0.55	0.09			
Benzene, 1,2,3-trimethyl-				0.21	1.01	1.25				
AlkylBenzenes (36 min - 40 min)							183.97	242.42		
TMPD-MIB	0.96	0.92	5.36	8.13	7.09	10.24	1.58	1.53	17.66	26.69
TMPD-DIB	4.15	5.19	406.42	519.43	307.18	389.71	9.59	14.21	429.19	565.42
Acetophenone	5.77	4.35								
Cyclotrisiloxane, hexamethyl-		0.04	0.38	0.28	0.83	0.74	0.82	0.85	1.95	0.84
Cyclotetrasiloxane, octamethyl-	0.16	0.12	0.06	0.05	0.13	0.24	0.19	0.18	0.35	0.21
Dimethyl methylphosphonate									8.84	5.00
1R-.alpha.-Pinene	0.53	0.49	90.40	82.17	103.11	102.67	28.71	19.36	69.10	73.00
3-Carene			2.09	2.17	4.91	5.59	3.28	2.72	9.98	11.06
beta.-Pinene	0.28	0.29	9.54	9.40	13.89	14.93	3.78	2.84	10.77	11.75
D-Limonene			3.09	3.22	3.71	4.52	1.12	0.87	5.09	6.15

Table 9. Whole Trailer Emission Rates Normalized to Floor Area (µg m^{-2} h^{-1})

	Trailers							
	Duchmen		Pilgrim		Coachmen		Cavalier	
Target Compound	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**
Acetic acid	36.57	55.37	25.89	44.12	8.31	18.36	35.18	48.05
Phenol	12.93	19.11	11.61	16.94	14.71	19.00	12.60	19.67
1-Hexanol, 2-ethyl-	0.73	1.43	0.58	1.18		0.39	1.89	3.11
Formaldehyde	199.90	257.26	173.76	267.13	265.82	347.05	260.97	315.12
Acetaldehyde	6.38	16.17	3.83	9.62	5.77	15.46	4.16	12.41
Hexanal	6.59	9.70	6.56	9.03	5.96	6.26	13.78	17.55
Octanal	2.60	3.97	1.51	2.21	1.58	2.11	2.53	3.48
Benzaldehyde	0.86	1.48		0.40			0.60	1.46
Nonanal	3.69	6.56	2.85	3.43	4.20	5.49	3.76	6.38
Dodecane	0.14	0.22	3.23	4.36	0.27		0.50	0.75
Tridecane	5.96	12.54	38.21	51.31		1.00	16.12	24.09
Tetradecane	13.58	19.96	27.51	36.05	24.82	33.01	15.13	22.53
Pentadecane	3.17	5.02	2.41	3.50	16.36	21.72	2.20	3.67
Hexadecane	0.79	1.21	0.57	0.98	3.53	4.91	0.72	1.22
Benzene			0.04					
Toluene	1.47	0.83	0.35	0.30	0.92	0.41	0.58	0.53
Ethylbenzene	0.19	0.10	0.13	0.11	0.25	0.12	0.24	0.24
p-Xylene	0.21	0.16	0.13	0.11	0.35	0.18	0.14	0.11
Styrene	4.84	2.19	4.15	3.23	3.63	1.25	7.95	6.80
Benzene, propyl-					0.45			
Benzene, 1,3,5-trimethyl-	0.05	0.07	0.13	0.16	0.07			
Benzene, 1,2,3-trimethyl-		0.11	0.29	0.36				
AlkylBenzenes (36 min - 40 min)					147.77	194.72		
TMPD-MIB	2.84	4.30	2.05	2.96	1.27	1.23	7.00	10.57
TMPD-DIB	214.88	274.63	88.74	112.58	7.70	11.41	170.01	223.97
Acetophenone								
Cyclotrisiloxane, hexamethyl-	0.20	0.15	0.24	0.21	0.66	0.68	0.77	0.33
Cyclotetrasiloxane, octamethyl-	0.03	0.03	0.04	0.07	0.16	0.15	0.14	0.08
Dimethyl methylphosphonate							3.50	1.98
1R-.alpha.-Pinene	47.79	43.44	29.79	29.66	23.06	15.55	27.37	28.92
3-Carene	1.10	1.15	1.42	1.62	2.63	2.19	3.95	4.38
beta.-Pinene	5.04	4.97	4.01	4.31	3.03	2.28	4.27	4.65
D-Limonene	1.63	1.70	1.07	1.31	0.90	0.70	2.01	2.44

Table 10. Material Specific Emission Factors (μg m^{-2} h^{-1}) for the Dutchmen trailer

Target Compound	bed deck	cabinet wall	cabinet end	carpet	ceiling	counter top	door interior	seat cushion	sub floor	trim	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results provided)											
Phenol	0.93	0.74	0.28	32.19	5.70	0.69	4.48	33.84	3.03	0.48	25.51	4.42
1-Hexanol, 2-ethyl-	0.56		0.77	0.99	0.87		0.24	9.19	0.98	0.48	1.47	0.85
Formaldehyde	4.11	17.70	5.21	42.41		11.18	45.64	69.19	4.31	10.98		10.89
Acetaldehyde				4.98		2.34	0.12	6.13	11.43	4.69		
Hexanal	0.85		0.47	10.89	0.59	0.74	1.86	1.08	8.69	0.83	3.22	2.21
Octanal				8.18								
Benzaldehyde	0.60	0.47		24.04	0.28	1.79	0.23	2.35	0.26		1.02	0.82
Nonanal	1.53	0.05	6.84	13.24	1.90	0.73	1.40	25.19	2.63		3.84	10.79
Dodecane									0.86		0.93	
Tridecane	0.25		0.86	16.47	1.07		3.33	10.78	16.82		37.66	0.92
Tetradecane	0.36			44.25	6.57		8.34	31.32	45.17	0.69	96.38	2.12
Pentadecane				9.84	3.02		2.87	9.08	37.01		78.54	1.02
Hexadecane	0.30	0.31		1.93	1.37		1.63	2.00	6.86		12.66	0.41
Benzene	0.42		0.25	1.18		0.28	0.13	0.40		0.06		1.70
Toluene	1.36	0.74	0.81	2.26	1.42	0.69	0.80	0.09	2.46	0.73	0.61	1.16
Ethylbenzene				0.59			0.01	0.10				
p-Xylene				1.41			0.03	0.35				0.59
Styrene				0.69			0.02	0.15				
Benzene, propyl-							0.03	0.08				
Benzene, 1,3,5-trimethyl-				0.17				0.14				
Benzene, 1,2,3-trimethyl-												
AlkylBenzenes (36 min - 40 min)												
TMPD-MIB		0.32		6.92	2.64	2.11	69.71	10.07	3.11		16.87	1.37
TMPD-DIB	6.05	30.55	2.44	662.64	468.43		368.54	844.73	262.52	2.64	2078.7	144.41
Acetophenone	0.94	1.12		7.10	0.30	1.41	0.21	0.43			0.41	0.46
Cyclotrisiloxane, hexamethyl-			0.11	7.25	7.39	5.63		1.44	5.38		7.87	3.48
Cyclotetrasiloxane, octamethyl-			0.36	1.01	1.70	0.64		0.38	1.61	0.09	1.56	0.21
Dimethyl methylphosphonate												
1R-.alpha.-Pinene	1.65	1.04	0.99	3.49	2.07	0.85	0.79		8.36	1.79	2.95	1.00
3-Carene				0.34								
beta.-Pinene	1.15	0.85		0.69	1.61	1.11	0.43		5.19	1.55	1.06	0.86
D-Limonene				1.30				0.49			0.46	27.72

Table 11. Material Specific Emission Factors (µg m^{-2} h^{-1}) for the Pilgrim trailer

Target Compound	bed deck	cabinet	carpet	ceiling	counter top	curtain	door interior	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results provided)										
Phenol	26.00	7.24	69.56	6.91	0.34	97.16	0.33	163.73	1.99	26.89	4.34
1-Hexanol, 2-ethyl-	0.58	0.20	0.71	1.26	0.60		0.01	3.24	0.81	0.74	0.80
Formaldehyde	136.24	419.13	57.62	22.07	4.97	323.34	14.32	409.91	14.80	1.69	33.73
Acetaldehyde	3.16	8.09	0.16				6.38		9.53		
Hexanal	27.78	0.64	1.89	0.49	0.73	0.46	0.78	9.52	3.32	3.73	0.37
Octanal			12.54								
Benzaldehyde	1.60	0.91	6.60	0.12	0.30	0.93	0.01	4.14	0.01	0.29	0.72
Nonanal	5.18	0.92	12.53	3.93	2.09	1.51		10.87	1.33		1.21
Dodecane	1.94		9.23	0.62				16.12	2.86	14.14	0.62
Tridecane	31.38	11.50	148.92	15.27	0.26	3.10	5.37	296.12	42.26	105.25	10.63
Tetradecane	41.73	17.89	121.59	30.63		14.20	10.62	234.82	34.34	62.10	13.46
Pentadecane	4.98	2.76	14.14	5.11	0.29	4.41	1.60	18.06	3.82	4.48	2.61
Hexadecane	1.29	2.40	2.60	2.29	0.23	2.41	0.60	3.84	1.12	1.46	1.30
Benzene	0.43	0.33	0.12	0.00	1.55	0.21	0.40	1.21	0.58		0.24
Toluene	2.61	1.73	0.06	1.21	0.85		0.83	3.71	1.66	0.48	1.18
Ethylbenzene			0.08		0.02		0.03	0.50			
p-Xylene			0.20		0.08		0.04	1.11			
Styrene			0.39		0.22	0.05	0.03	1.66			
Benzene, propyl-							0.02				
Benzene, 1,3,5-trimethyl-			0.13					0.39			
Benzene, 1,2,3-trimethyl-			0.38					1.07			
AlkylBenzenes (36 min - 40 min)											
TMPD-MIB	2.30	1.69	6.44	4.13	9.51	4.98	0.58	12.26	5.89	5.38	1.63
TMPD-DIB	143.11	241.29	325.60	502.75	9.47	421.53	35.94	879.99	434.74	924.84	221.30
Acetophenone	1.04	1.28	1.98	0.21	0.12	0.52	0.13	1.07		0.52	0.97
Cyclotrisiloxane, hexamethyl-	2.53	3.28		2.95	13.15			10.70	3.09	3.22	
Cyclotetrasiloxane, octamethyl-	1.23	0.62		0.94	1.70			2.12	1.13	0.79	
Dimethyl methylphosphonate			0.33					0.42			
1R-.alpha.-Pinene	7.80	3.74	2.58	2.90	1.89		0.11	10.16	4.27	1.34	1.90
3-Carene			1.56					1.89			
beta.-Pinene	8.24	3.64	0.68	2.03	1.14			4.24	2.59	0.78	1.33
D-Limonene	1.27		2.02				0.13	2.96			

Table 12. Material Specific Emission Factors (µg m^{-2} h^{-1}) for the Coachman trailer

Target Compound	bed deck	bench seat	cabinet wall	ceiling	counter top	curtain	door interior	end bench	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results provided)											
Phenol	14.06	2.98	0.50	11.08	0.36	24.23	1.79	0.86	63.42	196.86	17.85	2.16
1-Hexanol, 2-ethyl-	0.30	0.61	0.32	0.99	0.91		2.90	1.23	2.00	0.48	0.57	0.54
Formaldehyde	41.51	232.85	174.72	25.11	7.86	14.35	35.88	33.30	151.00	3.61		59.70
Acetaldehyde	12.84	2.43				2.47	0.75	1.66	4.50	18.33		
Hexanal	10.91	3.05	0.56	0.49	2.50	0.16	9.45	5.02	5.24	107.27	1.02	0.29
Octanal							0.57					
Benzaldehyde	0.82		0.05	0.34	1.48	0.16	0.02		1.60	14.56	1.42	0.60
Nonanal		3.40	0.96	7.60	1.07	0.04	29.72	1.43	5.36	1.46	0.86	0.71
Dodecane							1.47			6.54		
Tridecane		0.79		0.23		0.07	54.90		3.53	138.20	4.09	
Tetradecane	58.11	10.79	3.60	24.05		0.33	5.28	6.74	87.71	2055.8	82.78	3.79
Pentadecane	41.24	9.74	3.53	27.36		0.59	6.62	5.76	61.56	1206.4	52.58	3.78
Hexadecane	4.77	2.21	1.27	8.26		0.43	1.69	1.47	12.35	239.65	10.98	1.93
Benzene	0.21	0.47	0.64	0.22	1.52	13.29	0.54	0.04	0.57	0.08		0.08
Toluene	2.39	1.27	1.87	1.18	2.04		2.15	2.34	2.72	2.19	0.68	0.80
Ethylbenzene							0.02		0.41			
p-Xylene						0.02	0.07		1.00	1.14		
Styrene						0.00	0.02		0.63		0.42	
Benzene, propyl-												
Benzene, 1,3,5-trimethyl-												
Benzene, 1,2,3-trimethyl-												
AlkylBenzenes (36 min - 40 min)												
TMPD-MIB	2.12	1.32		1.69	2.14			0.34	4.62	15.95	1.75	0.32
TMPD-DIB	11.30	4.70	1.26	26.38		1.59	1.97	1.22	26.21	1026.5	102.10	3.79
Acetophenone	0.22			0.49	1.08	0.14	0.26		0.46	1.15	0.19	0.71
Cyclotrisiloxane, hexamethyl-			2.31						3.74	0.58	4.13	
Cyclotetrasiloxane, octamethyl-		0.48	0.32				0.19	0.43	1.66	1.25	0.83	
Dimethyl methylphosphonate												
1R-.alpha.-Pinene	4.92	2.90	3.46	2.37	1.17		1.51	4.99	7.89	31.73	2.06	1.37
3-Carene									2.10	1.34		
beta.-Pinene	5.56	1.92	2.29	2.63	1.48		0.92	2.94	2.73	15.71	1.00	1.15
D-Limonene	0.75					0.10	0.22		1.70	6.58		

Table 13. Material Specific Emission Factors (μg m^{-2} h^{-1}) for the Cavalier trailer

Target Compound	cabinet door	cabinet wall	ceiling	counter top	door interior	seat bottom	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results provided)									
Phenol	0.79	1.15	5.70	0.43	1.19	15.30	85.15	47.76	21.87	7.16
1-Hexanol, 2-ethyl-	0.52		0.75	0.23	0.00	3.08	17.32	0.76	0.80	1.26
Formaldehyde	91.84	487.48	20.12	9.69	35.67	292.94	30.35	416.33	13.85	26.02
Acetaldehyde	7.14	1.57		2.12	6.51	3.11		16.44	3.41	
Hexanal	3.24	1.08	0.48	1.27	3.83	11.72	1.56	81.60	8.10	0.98
Octanal								2.32		
Benzaldehyde		0.07	0.29	0.85	0.75	2.75	4.02	3.46	1.78	0.47
Nonanal	1.37		2.75	0.54	0.26	8.61	13.01	6.33	2.93	5.25
Dodecane						1.24	1.54	5.79	1.11	
Tridecane	3.43	0.79	5.48	0.02	0.96	28.07	87.37	238.22	46.57	3.20
Tetradecane	6.01	3.34	14.66		5.46	44.59	144.40	230.93	46.92	6.08
Pentadecane	1.49	0.86	4.12		2.01	9.14	22.51	22.33	6.90	1.98
Hexadecane	0.75		2.22	0.12	0.74	3.72	6.29	6.49	3.31	1.61
Benzene	0.51	0.15	0.44	0.28	0.44	3.86	0.76	0.20		0.13
Toluene	0.92	0.99	0.79	0.62	1.13	5.10	0.80	1.50		0.93
Ethylbenzene				0.00	0.02	0.99	0.36			
p-Xylene				0.00	0.02	2.58	1.16			
Styrene				0.36			0.27			
Benzene, propyl-				0.11			0.19			
Benzene, 1,3,5-trimethyl-							0.24			
Benzene, 1,2,3-trimethyl-										
AlkylBenzenes (36 min - 40 min)										
TMPD-MIB	2.53	1.97	10.45	4.42	0.74	11.52	87.68	47.10	20.25	6.33
TMPD-DIB	81.25	77.71	770.57	0.26	139.29	938.76	1813.0	2919.8	2250.9	481.22
Acetophenone			0.29	0.17	0.32	1.01	2.81	0.90	0.44	0.48
Cyclotrisiloxane, hexamethyl-	10.60			10.50	6.97		11.36		5.29	
Cyclotetrasiloxane, octamethyl-	1.70	0.33		1.30	0.72	0.36	1.36	0.49	0.76	
Dimethyl methylphosphonate										
1R-.alpha.-Pinene	1.10	1.52	1.13	1.09	0.63	6.17		50.24	1.67	1.55
3-Carene							0.06	0.81		
beta.-Pinene	0.81	0.91	1.17	0.48		4.65		11.38	0.63	1.99
D-Limonene						2.33	0.89	1.46		

Table 14. Material Emission Factors Normalized to Whole Trailer Floor Area (µg m^{-2} h^{-1}) for the Dutchmen trailer

Target Compound	bed deck	cabinet wall	cabinet end	carpet	ceiling	counter top	door interior	seat cushion	sub floor	trim	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results are provided)											
Phenol	0.28	1.10	0.04	13.24	6.68	0.09	0.62	4.20	3.55	0.03	22.40	13.19
1-Hexanol, 2-ethyl-	0.17		0.10	0.41	1.02		0.03	1.14	1.15	0.03	1.29	2.54
Formaldehyde	1.24	26.34	0.68	17.44		1.51	6.31	8.58	5.05	0.64		32.48
Acetaldehyde				2.05		0.32	0.02	0.76	13.38	0.27		
Hexanal	0.26		0.06	4.48	0.70	0.10	0.26	0.13	10.18	0.05	2.83	6.60
Octanal				3.37								
Benzaldehyde	0.18	0.71		9.89	0.33	0.24	0.03	0.29	0.30		0.89	2.45
Nonanal	0.46	0.08	0.90	5.44	2.22	0.10	0.19	3.12	3.08		3.37	32.20
Dodecane									1.00		0.82	
Tridecane	0.08		0.11	6.77	1.25		0.46	1.34	19.69		33.06	2.74
Tetradecane	0.11			18.19	7.69		1.15	3.88	52.90	0.04	84.61	6.34
Pentadecane				4.05	3.54		0.40	1.13	43.34		68.95	3.04
Hexadecane	0.09	0.47		0.79	1.61		0.23	0.25	8.03		11.11	1.23
Benzene	0.13		0.03	0.49		0.04	0.02	0.05		0.00		5.06
Toluene	0.41	1.10	0.11	0.93	1.67	0.09	0.11	0.01	2.88	0.04	0.54	3.46
Ethylbenzene				0.24			0.00	0.01				
p-Xylene				0.58			0.00	0.04				1.77
Styrene				0.28			0.00	0.02				
Benzene, propyl-							0.00	0.01				
Benzene, 1,3,5-trimethyl-				0.07				0.02				
Benzene, 1,2,3-trimethyl-												
AlkylBenzenes (36 min - 40 min)												
TMPD-MIB		0.48		2.85	3.10	0.28	9.64	1.25	3.65		14.81	4.10
TMPD-DIB	1.83	45.46	0.32	272.48	548.52		50.95	104.75	307.41	0.15	1824.8	430.71
Acetophenone	0.28	1.67		2.92	0.36	0.19	0.03	0.05			0.36	1.39
Cyclotrisiloxane, hexamethyl-			0.01	2.98	8.65	0.76		0.18	6.31		6.91	10.39
Cyclotetrasiloxane, octamethyl-			0.05	0.41	1.99	0.09		0.05	1.89	0.01	1.37	0.63
Dimethyl methylphosphonate												
1R-.alpha.-Pinene	0.50	1.55	0.13	1.43	2.42	0.11	0.11		9.79	0.10	2.59	2.97
3-Carene				0.14								
beta.-Pinene	0.35	1.26		0.28	1.88	0.15	0.06		6.08	0.09	0.93	2.55
D-Limonene				0.53				0.06			0.41	82.67

Table 15. Material Emission Factors Normalized to Whole Trailer Floor Area (µg m^{-2} h^{-1}) for the Pilgrim trailer

Target Compound	bed deck	cabinet	carpet	ceiling	counter top	curtain	door interior	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results are provided)										
Phenol	4.97	4.69	25.17	6.61	0.03	8.41	0.03	16.18	1.99	17.16	8.68
1-Hexanol, 2-ethyl-	0.11	0.13	0.26	1.21	0.05		0.00	0.32	0.81	0.48	1.61
Formaldehyde	26.06	271.44	20.85	21.09	0.38	27.98	1.44	40.51	14.80	1.08	67.48
Acetaldehyde	0.60	5.24	0.06				0.64		9.53		
Hexanal	5.31	0.42	0.68	0.47	0.06	0.04	0.08	0.94	3.32	2.38	0.74
Octanal			4.54								
Benzaldehyde	0.31	0.59	2.39	0.11	0.02	0.08	0.00	0.41	0.01	0.18	1.43
Nonanal	0.99	0.60	4.54	3.75	0.16	0.13		1.07	1.33		2.42
Dodecane	0.37		3.34	0.59				1.59	2.86	9.03	1.24
Tridecane	6.00	7.45	53.89	14.60	0.02	0.27	0.54	29.26	42.26	67.17	21.26
Tetradecane	7.98	11.59	44.00	29.28		1.23	1.07	23.21	34.34	39.63	26.93
Pentadecane	0.95	1.79	5.12	4.89	0.02	0.38	0.16	1.78	3.82	2.86	5.22
Hexadecane	0.25	1.56	0.94	2.19	0.02	0.21	0.06	0.38	1.12	0.93	2.59
Benzene	0.08	0.22	0.04	0.00	0.12	0.02	0.04	0.12	0.58		0.48
Toluene	0.50	1.12	0.02	1.16	0.07		0.08	0.37	1.66	0.30	2.36
Ethylbenzene			0.03		0.00		0.00	0.05			
p-Xylene			0.07		0.01		0.00	0.11			
Styrene			0.14		0.02	0.00	0.00	0.16			
Benzene, propyl-							0.00				
Benzene, 1,3,5-trimethyl-			0.05					0.04			
Benzene, 1,2,3-trimethyl-			0.14					0.11			
AlkylBenzenes (36 min - 40 min)											
TMPD-MIB	0.44	1.10	2.33	3.95	0.73	0.43	0.06	1.21	5.89	3.43	3.26
TMPD-DIB	27.37	156.27	117.82	480.51	0.72	36.47	3.61	86.96	434.74	590.25	442.78
Acetophenone	0.20	0.83	0.72	0.20	0.01	0.05	0.01	0.11		0.33	1.95
Cyclotrisiloxane, hexamethyl-	0.48	2.12		2.82	1.01			1.06	3.09	2.06	
Cyclotetrasiloxane, octamethyl-	0.24	0.40		0.90	0.13			0.21	1.13	0.50	
Dimethyl methylphosphonate			0.12					0.04			
1R-.alpha.-Pinene	1.49	2.42	0.93	2.77	0.14		0.01	1.00	4.27	0.86	3.80
3-Carene			0.57					0.19			
beta.-Pinene	1.58	2.36	0.24	1.94	0.09			0.42	2.59	0.50	2.65
D-Limonene	0.24		0.73				0.01	0.29			

Table 16. Material Emission Factors Normalized to Whole Trailer Floor Area (µg m^{-2} h^{-1}) for the Coachmen trailer

Target Compound	bed deck	bench seat	cabinet wall	ceiling	counter top	curtain	door interior	end bench	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results are provided)											
Phenol	1.69	0.72	0.15	11.88	0.03	3.67	0.08	0.03	5.54	196.83	17.85	6.07
1-Hexanol, 2-ethyl-	0.04	0.15	0.10	1.06	0.07		0.13	0.05	0.18	0.48	0.57	1.51
Formaldehyde	5.00	56.30	53.48	26.91	0.63	2.17	1.56	1.35	13.19	3.61		167.99
Acetaldehyde	1.55	0.59				0.37	0.03	0.07	0.39	18.33		
Hexanal	1.31	0.74	0.17	0.52	0.20	0.02	0.41	0.20	0.46	107.26	1.02	0.81
Octanal							0.02					
Benzaldehyde	0.10		0.02	0.36	0.12	0.02	0.00		0.14	14.55	1.42	1.69
Nonanal		0.82	0.29	8.15	0.09	0.01	1.29	0.06	0.47	1.46	0.86	2.01
Dodecane							0.06			6.54		
Tridecane		0.19		0.24		0.01	2.39		0.31	138.18	4.09	
Tetradecane	7.00	2.61	1.10	25.79		0.05	0.23	0.27	7.66	2055.5	82.77	10.67
Pentadecane	4.97	2.35	1.08	29.33		0.09	0.29	0.23	5.38	1206.2	52.57	10.63
Hexadecane	0.58	0.53	0.39	8.85		0.07	0.07	0.06	1.08	239.62	10.98	5.44
Benzene	0.02	0.11	0.20	0.24	0.12	2.01	0.02	0.00	0.05	0.08		0.22
Toluene	0.29	0.31	0.57	1.26	0.16		0.09	0.10	0.24	2.19	0.68	2.26
Ethylbenzene							0.00		0.04			
p-Xylene						0.00	0.00		0.09	1.14		
Styrene						0.00	0.00		0.06		0.42	
Benzene, propyl-												
Benzene, 1,3,5-trimethyl-												
Benzene, 1,2,3-trimethyl-												
AlkylBenzenes (36 min - 40 min)												
TMPD-MIB	0.26	0.32		1.81	0.17			0.01	0.40	15.95	1.75	0.91
TMPD-DIB	1.36	1.14	0.39	28.28		0.24	0.09	0.05	2.29	1026.4	102.08	10.66
Acetophenone	0.03			0.53	0.09	0.02	0.01		0.04	1.15	0.19	2.01
Cyclotrisiloxane, hexamethyl-			0.71						0.33	0.58	4.13	
Cyclotetrasiloxane, octamethyl-		0.12	0.10				0.01	0.02	0.15	1.25	0.83	
Dimethyl methylphosphonate												
1R-.alpha.-Pinene	0.59	0.70	1.06	2.55	0.09		0.07	0.20	0.69	31.72	2.06	3.86
3-Carene									0.18	1.34		
beta.-Pinene	0.67	0.47	0.70	2.82	0.12		0.04	0.12	0.24	15.71	1.00	3.24
D-Limonene	0.09					0.01	0.01		0.15	6.58		

Table 17. Material Emission Factors Normalized to Whole Trailer Floor Area (µg m^{-2} h^{-1}) for the Cavalier trailer

Target Compound	cabinet door	cabinet wall	ceiling	counter top	door interior	seat bottom	seat cushion	sub floor	vinyl floor	wall
acetic acid	(acetic acid has not been quantified in the material samples so no results are provided)									
Phenol	0.01	1.03	5.42	0.02	0.11	5.20	8.80	47.77	21.87	21.73
1-Hexanol, 2-ethyl-	0.00		0.71	0.01	0.00	1.05	1.79	0.76	0.80	3.84
Formaldehyde	0.76	435.14	19.17	0.56	3.32	99.60	3.14	416.39	13.86	78.97
Acetaldehyde	0.06	1.40		0.12	0.61	1.06		16.44	3.41	
Hexanal	0.03	0.96	0.46	0.07	0.36	3.99	0.16	81.61	8.10	2.97
Octanal								2.32		
Benzaldehyde		0.06	0.27	0.05	0.07	0.93	0.42	3.46	1.78	1.43
Nonanal	0.01		2.62	0.03	0.02	2.93	1.34	6.33	2.93	15.95
Dodecane						0.42	0.16	5.79	1.11	
Tridecane	0.03	0.70	5.22	0.00	0.09	9.54	9.03	238.26	46.58	9.70
Tetradecane	0.05	2.98	13.96		0.51	15.16	14.92	230.97	46.93	18.44
Pentadecane	0.01	0.77	3.92		0.19	3.11	2.33	22.34	6.90	6.00
Hexadecane	0.01		2.11	0.01	0.07	1.26	0.65	6.49	3.31	4.88
Benzene	0.00	0.14	0.42	0.02	0.04	1.31	0.08	0.20		0.38
Toluene	0.01	0.88	0.75	0.04	0.11	1.73	0.08	1.50		2.84
Ethylbenzene				0.00	0.00	0.34	0.04			
p-Xylene				0.00	0.00	0.88	0.12			
Styrene				0.02			0.03			
Benzene, propyl-				0.01			0.02			
Benzene, 1,3,5-trimethyl-							0.03			
Benzene, 1,2,3-trimethyl-										
AlkylBenzenes (36 min - 40 min)										
TMPD-MIB	0.02	1.76	9.96	0.25	0.07	3.92	9.06	47.11	20.26	19.22
TMPD-DIB	0.67	69.36	734.00	0.01	12.98	319.20	187.30	2920.3	2251.3	1460.6
Acetophenone			0.28	0.01	0.03	0.34	0.29	0.90	0.44	1.47
Cyclotrisiloxane, hexamethyl-	0.09			0.60	0.65		1.17		5.29	
Cyclotetrasiloxane, octamethyl-	0.01	0.29		0.07	0.07	0.12	0.14	0.49	0.76	
Dimethyl methylphosphonate										
1R-.alpha.-Pinene	0.01	1.35	1.08	0.06	0.06	2.10		50.25	1.67	4.71
3-Carene							0.01	0.81		
beta.-Pinene	0.01	0.81	1.12	0.03		1.58		11.38	0.63	6.05
D-Limonene						0.79	0.09	1.47		

Table 18. Total (μg m^{-2} h^{-1}) and Percent Contribution to Area Normalized Whole Trailer Emission Rates for the Duchmen

Target Compound	Total* μg m^{-2} h^{-1}	cabinet wall	carpet	ceiling	counter top	door interior	seat cushion	trim	vinyl floor	wall
acetic acid										
Phenol	62		21%	11%			7%		36%	21%
1-Hexanol, 2-ethyl-	7		6%	15%			17%		19%	38%
Formaldehyde	95	28%	18%			7%	9%			34%
Acetaldehyde	3		60%		9%		22%	8%		
Hexanal	15		29%						18%	43%
Octanal	3		100%							
Benzaldehyde	15		66%						6%	16%
Nonanal	48		11%				6%		7%	67%
Dodecane	1								100%	
Tridecane	46		15%						72%	6%
Tetradecane	122		15%	6%					69%	5%
Pentadecane	81								85%	
Hexadecane	16		5%	10%					70%	8%
Benzene	6		8%							87%
Toluene	8	13%	11%	20%					6%	41%
Ethylbenzene										
p-Xylene	2		24%							74%
Styrene										
Benzene, propyl-										
Benzene, 1,3,5-trimethyl-										
Benzene, 1,2,3-trimethyl-										
AlkylBenzenes (36 min - 40 min)										
TMPD-MIB	36		8%	8%		26%			41%	11%
TMPD-DIB	3280		8%	17%					56%	13%
Acetophenone	7	23%	40%							19%
Cyclotrisiloxane, hexamethyl-	30		10%	29%					23%	35%
Cyclotetrasiloxane, octamethyl-	5		9%	43%					30%	14%
Dimethyl methylphosphonate										
1R-.alpha.-Pinene	12	13%	12%	20%					22%	25%
3-Carene										
beta.-Pinene	8	17%		25%					12%	34%
D-Limonene	84									99%

* Calculated percentages exclude contribution from subfloor material.

Table 19. Total (µg m^{-2} h^{-1}) and Percent Contribution to Area Normalized Whole Trailer Emission Rates for the Pilgrim

Target Compound	Total* µg m^{-2} h^{-1}	bed deck	cabinet	carpet	ceiling	counter top	curtain	door interior	seat cushion	vinyl floor	wall
acetic acid											
Phenol	92	5%	5%	27%	7%		9%		18%	19%	9%
1-Hexanol, 2-ethyl-	4			6%	29%				8%	11%	39%
Formaldehyde	478	5%	57%				6%		8%		14%
Acetaldehyde	7	9%	80%					10%			
Hexanal	11	48%		6%					8%	21%	7%
Octanal	5			100%							
Benzaldehyde	6	6%	11%	43%					7%		26%
Nonanal	14	7%		33%	27%				8%		18%
Dodecane	16			21%					10%	56%	8%
Tridecane	200			27%	7%				15%	34%	11%
Tetradecane	185		6%	24%	16%				13%	21%	15%
Pentadecane	23		8%	22%	21%				8%	12%	23%
Hexadecane	9		17%	10%	24%					10%	28%
Benzene	1	7%	19%			11%			11%		43%
Toluene	6	8%	19%		19%				6%	5%	39%
Ethylbenzene											
p-Xylene											
Styrene											
Benzene, propyl-											
Benzene, 1,3,5-trimethyl-											
Benzene, 1,2,3-trimethyl-											
AlkylBenzenes (36 min - 40 min)											
TMPD-MIB	17		6%	14%	23%				7%	20%	19%
TMPD-DIB	1943		8%	6%	25%					30%	23%
Acetophenone	4		19%	16%						8%	44%
Cyclotrisiloxane, hexamethyl-	10	5%	22%		30%	11%			11%	22%	
Cyclotetrasiloxane, octamethyl-	2	10%	17%		38%	5%			9%	21%	
Dimethyl methylphosphonate											
1R-.alpha.-Pinene	13	11%	18%	7%	21%				7%	6%	28%
3-Carene	1			75%					25%		
beta.-Pinene	10	16%	24%		20%					5%	27%
D-Limonene	1	19%		57%					23%		

* Calculated percentages exclude contribution from subfloor material.

Table 20. Total ($\mu g\ m^{-2}\ h^{-1}$) and Percent Contribution to Area Normalized Whole Trailer Emission Rates for the Coachmen

Target Compound	Total* $\mu g\ m^{-2}\ h^{-1}$	bed deck	bench seat	cabinet wall	ceiling	curtain	door interior	seat cushion	vinyl floor	wall
acetic acid										
Phenol	48				25%	8%		12%	37%	13%
1-Hexanol, 2-ethyl-	4				28%				15%	39%
Formaldehyde	329		17%	16%	8%					51%
Acetaldehyde	3	52%	20%			12%		13%		
Hexanal	6	22%	13%		9%		7%	8%	17%	14%
Octanal										
Benzaldehyde	4				9%				37%	44%
Nonanal	14		6%		58%		9%		6%	14%
Dodecane										
Tridecane	7						33%		57%	
Tetradecane	138	5%			19%			6%	60%	8%
Pentadecane	107				27%			5%	49%	10%
Hexadecane	28				32%				39%	19%
Benzene	3			7%	8%	67%				7%
Toluene	6		5%	10%	21%				11%	38%
Ethylbenzene										
p-Xylene										
Styrene										
Benzene, propyl-										
Benzene, 1,3,5-trimethyl-										
Benzene, 1,2,3-trimethyl-										
AlkylBenzenes (36 min - 40 min)										
TMPD-MIB	6		6%		32%			7%	31%	16%
TMPD-DIB	147				19%				70%	7%
Acetophenone	3				18%				6%	69%
Cyclotrisiloxane, hexamethyl-	5			14%				6%	80%	
Cyclotetrasiloxane, octamethyl-	1		10%	8%				12%	68%	
Dimethyl methylphosphonate										
1R-.alpha.-Pinene	12		6%	9%	21%			6%	17%	32%
3-Carene										
beta.-Pinene	9	7%		7%	30%				11%	34%
D-Limonene										

* Calculated percentages exclude contribution from subfloor material.

Table 21. Total (µg m^{-2} h^{-1}) and Percent Contribution to Area Normalized Whole Trailer Emission Rates for the Cavalier

Target Compound	Total* µg m^{-2} h^{-1}	cabinet wall	ceiling	counter top	door interior	seat bottom	seat cushion	vinyl floor	wall
acetic acid									
Phenol	64		8%			8%	14%	34%	34%
1-Hexanol, 2-ethyl-	8		9%			13%	22%	10%	47%
Formaldehyde	655	66%				15%			12%
Acetaldehyde	7	21%			9%	16%		51%	
Hexanal	17	6%				23%		47%	17%
Octanal									
Benzaldehyde	5		5%			19%	8%	36%	29%
Nonanal	26		10%			11%	5%	11%	62%
Dodecane	2					25%	9%	66%	
Tridecane	81		6%			12%	11%	58%	12%
Tetradecane	113		12%			13%	13%	42%	16%
Pentadecane	23		17%			13%	10%	30%	26%
Hexadecane	12		17%			10%	5%	27%	40%
Benzene	2	6%	18%			55%			16%
Toluene	6	14%	12%			27%			44%
Ethylbenzene									
p-Xylene	1					88%	12%		
Styrene									
Benzene, propyl-									
Benzene, 1,3,5-trimethyl-									
Benzene, 1,2,3-trimethyl-									
AlkylBenzenes (36 min - 40 min)									
TMPD-MIB	65		15%			6%	14%	31%	30%
TMPD-DIB	5035		15%			6%		45%	29%
Acetophenone	3		10%			12%	10%	15%	51%
Cyclotrisiloxane, hexamethyl-	8			8%	8%		15%	68%	
Cyclotetrasiloxane, octamethyl-	1	20%		5%		8%	10%	52%	
Dimethyl methylphosphonate									
1R-.alpha.-Pinene	11	12%	10%			19%		15%	43%
3-Carene									
beta.-Pinene	10	8%	11%			15%		6%	59%
D-Limonene	1					90%	10%		

* Calculated percentages exclude contribution from subfloor material.

Table 22. Comparison of Reconstructed Whole Trailer Emission Factors and Measured Emission Factors

	Duchmen		Pilgrim		Coachmen		Cavalier	
Target Compound	Material	Whole trailer	Material	Whole trailer	Material	Whole trailer	Material	Whole trailer
acetic acid	*	45.97	*	35.00	*	13.34	*	41.62
Phenol	62	16.02	92	14.27	48	16.85	64	16.14
1-Hexanol, 2-ethyl-	7	1.08	4	0.88	4	0.39	8	2.50
Formaldehyde	95	228.58	478	220.45	329	306.44	655	288.04
Acetaldehyde	3	11.28	7	6.72	3	10.61	7	8.29
Hexanal	15	8.15	11	7.80	6	6.11	17	15.67
Octanal	3	3.29	5	1.86	0	1.85	0	3.01
Benzaldehyde	15	1.17	6	0.40	4		5	1.03
Nonanal	48	5.12	14	3.14	14	4.85	26	5.07
Dodecane	1	0.18	16	3.79	0	0.27	2	0.62
Tridecane	46	9.25	200	44.76	7	1.00	81	20.11
Tetradecane	122	16.77	185	31.78	138	28.91	113	18.83
Pentadecane	81	4.09	23	2.96	107	19.04	23	2.93
Hexadecane	16	1.00	9	0.77	28	4.22	12	0.97
Benzene	6		1	0.04	3		2	
Toluene	8	1.15	6	0.33	6	0.66	6	0.55
Ethylbenzene	0	0.15	0	0.12	0	0.18	0	0.24
p-Xylene	2	0.18	0	0.12	0	0.27	1	0.13
Styrene	0	3.52	0	3.69	0	2.44	0	7.38
Benzene, propyl-	0		0		0	0.45	0	
Benzene, 1,3,5-trimethyl-	0	0.06	0	0.14	0	0.07	0	
Benzene, 1,2,3-trimethyl-	0	0.11	0	0.33	0		0	
AlkylBenzenes (36 min - 40 min)	*		*		*	171.25	*	
TMPD-MIB	36	3.57	17	2.50	6	1.25	65	8.78
TMPD-DIB	3280	244.75	1943	100.66	147	9.56	5035	196.99
Acetophenone	7		4		3		3	
Cyclotrisiloxane, hexamethyl-	30	0.17	10	0.23	5	0.67	8	0.55
Cyclotetrasiloxane, octamethyl-	5	0.03	2	0.05	1	0.15	1	0.11
Dimethyl methylphosphonate	0		0		0		0	2.74
1R-.alpha.-Pinene	12	45.62	13	29.72	12	19.31	11	28.14
3-Carene	0	1.12	1	1.52	0	2.41	0	4.17
beta.-Pinene	8	5.01	10	4.16	9	2.66	10	4.46
D-Limonene	84	1.67	1	1.19	0	0.80	1	2.23

* acetic acid and alkylbenzenes not yet quantified in the material specific emission factors

Table 23. Material specific aldehyde emissions from cabinetry, passage door, and subfloor used to fabricate a new manufactured house

	Emission factor (μg m^{-2} h^{-1})					
	Cabinetry Materials*				Passage	Plywood
Compound	PB Top	PB case	Hardboard	Stile	door	subfloor*
Formaldehyde	92,82	470	10	330	153	11,8
Acetaldehyde	38,40			20	11	19,10
Pentanal	51,42			36	8	28,25
Hexanal	249,199			260	42	169,161
2-Furaldehyde	6,5		72	7		
Heptanal	12,9			7		4,3
2-Heptenal	8,5			9		5,5
Benzaldehyde	16			42	3	5
Octanal	22,18			28		8,8
2-Octenal	19,12			29		12,11
Nonanal	19,16			40		21,22

*Values are presented for duplicate specimens separated by a comma. The data are for new material direct from factory as reported in Hodgson et. al. 2002

Table 24. Material specific emission factors of terpene hydrocarbons from indoor sources used to fabricate a new manufactured house

Compound	PB countertop* (μg m^{-2} h^{-1})	Cabinet frame lumber (μg m^{-2} h^{-1})	Plywood subfloor* (μg m^{-2} h^{-1})
a-Pinene	19,26	14	114,278
b-Pinene	7,7	17	29,69
d-Limonene	6,6	<3	29,113

* Values are presented for duplicate specimens separated by a comma. The data are for new material direct from factory as reported in Hodgson et. al. 2002

Table 25. Reported Formaldehyde Emission Factors from CARB's Battelle (1996) study[1].

Material	Emission Factor ($\mu g\ m^{-2}\ h^{-1}$)				Sample Size	Notes
	Mean	Median	Min	Max	N	
Hardwood Plywood	87	74	6.8	170	12	¼"-¾" stock HWPW and ½" HWPW-VC
Medium Density Fiberboard	293	288	210	385	6	⅝"-¾" MDF
MDF Cabinet Doors	420		364	535	2	
Particleboard	189	161	104	508	22	⅝'-3/4" industrial PB, ⅝" PB underlayment, and ⅝" mobile home decking
¼" Particleboard	1375		1170	1580	2	
Wallpaper	27					
Coated MDF Cabinet Doors	880		460	1300	2	
Coated PB – Paper Laminated	60	52	26	120	6	
Coated PB – Mobile Home Decking	44		35	52	2	
Coated PB – Melamine Laminated	20	11	2.2	86	12	
Coated PB – Rigid Vinyl	24		16	31	2	
Coated PB – Vinyl or Acrylic	4	2.7	1.3	8.6	8	
Interior Door – PB Core	11		7.0	15	2	

[1] Source: Appendix D Basis for Formaldehyde Emission Factors, Rulemaking to Consider Adoption of the Proposed Airborne Toxic Control Measure (ACTM) to Reduce Formaldehyde Emissions From Composite Wood Products, California Air Resources Board. April 2007. http://www.arb.ca.gov/regact/2007/compwood07/compwood07.htm

FIGURES

Figure 1. Preparation for indoor sampling in a THU. Half inch holes were drilled into the THU door for insertion of ¼" stainless steel sampling tubes. A sampling tube and sample pump are seen in the foreground*.*

Figure 2. Collection of indoor sample through the THU door.

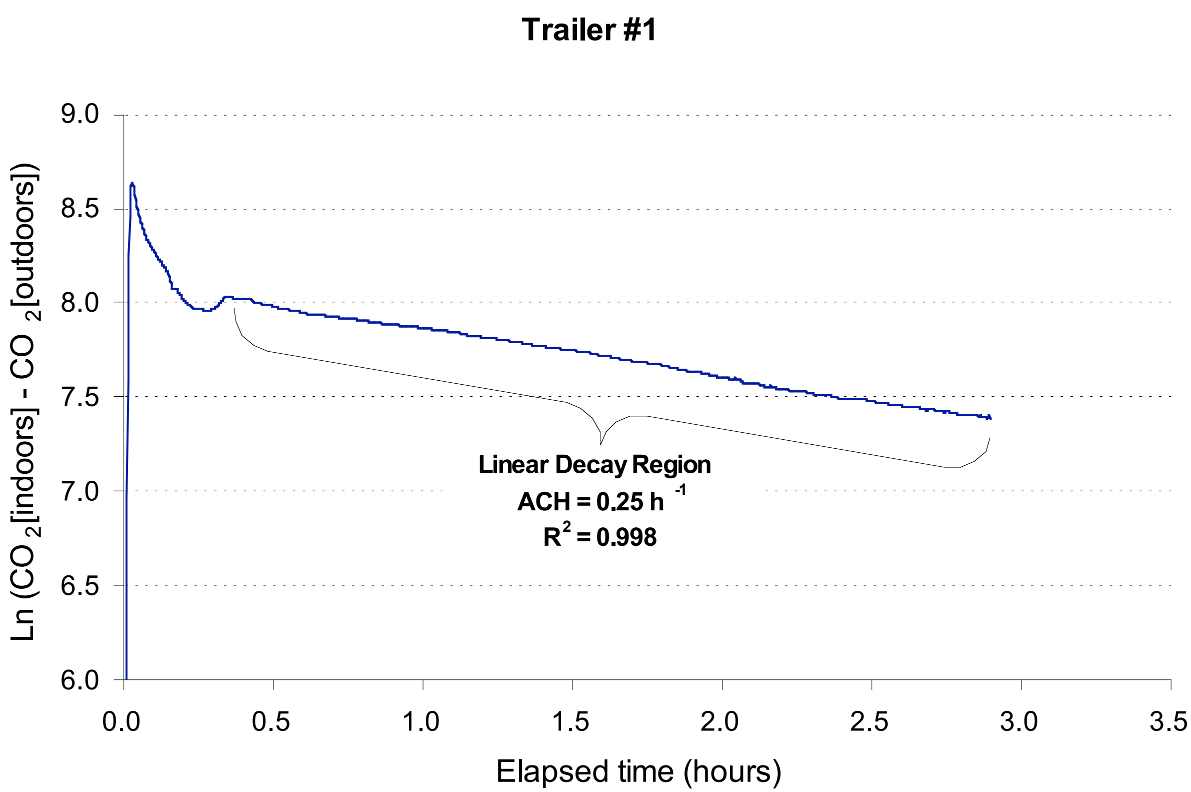

Figure 3 Example of tracer gas experiment determining ventilation rate in trailer showing initial stabilization period followed by the linear decay region. The ventilation rate is determined from the slope of the decay curve in the linear region as described in the text. The response shown here for Trailer 1 is typical of all the units tested.

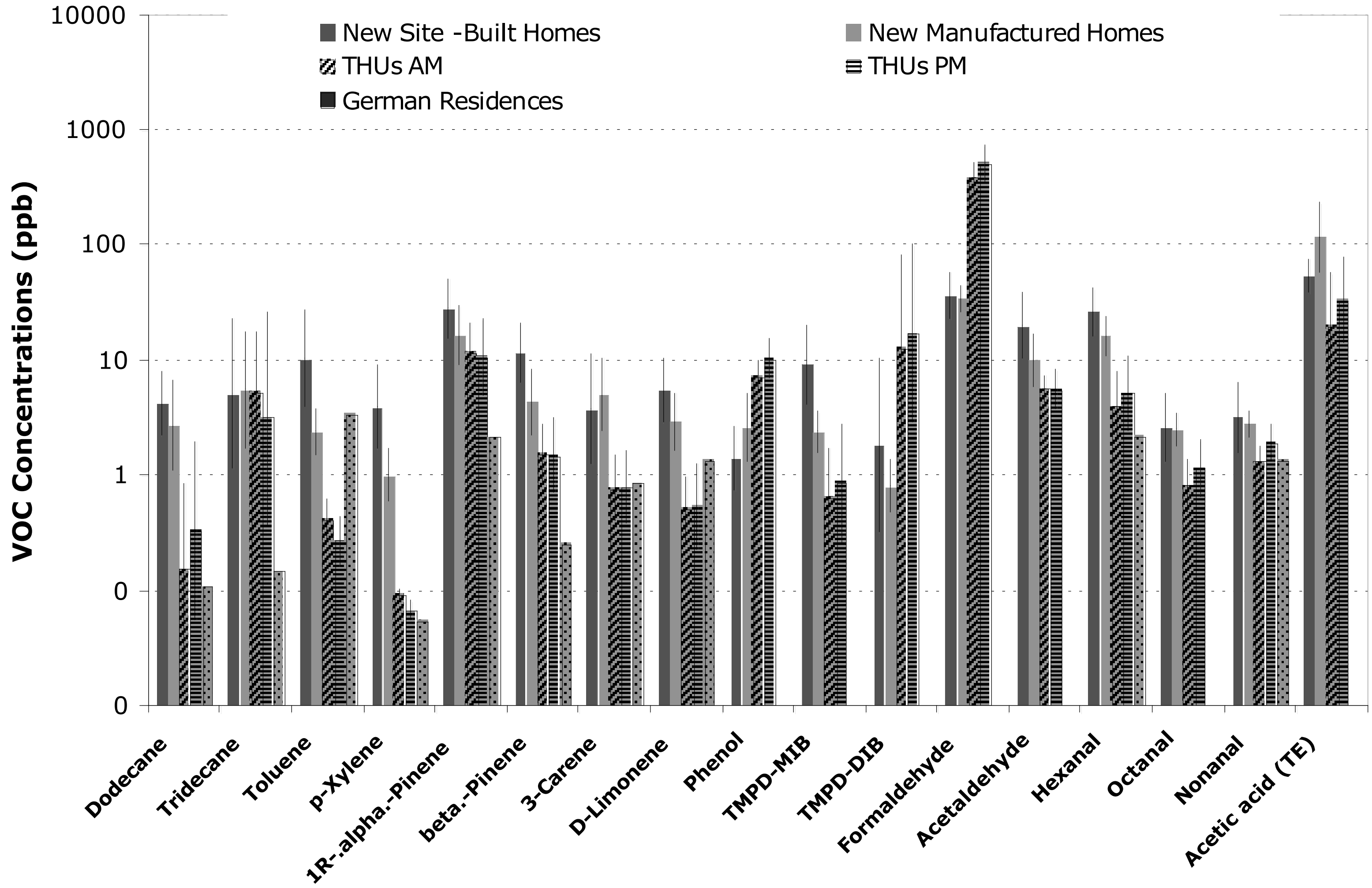

Figure 4. Comparison of indoor air concentration (ppm) data for new site-built and manufactured homes (Hodgson et. al., 2000), German residences (Hippelein, 2004) and the four THUs measured in the AM and the PM sampling events. The data are reported as geometric mean (GM) with error bars representing one geometric standard deviation (GSD).

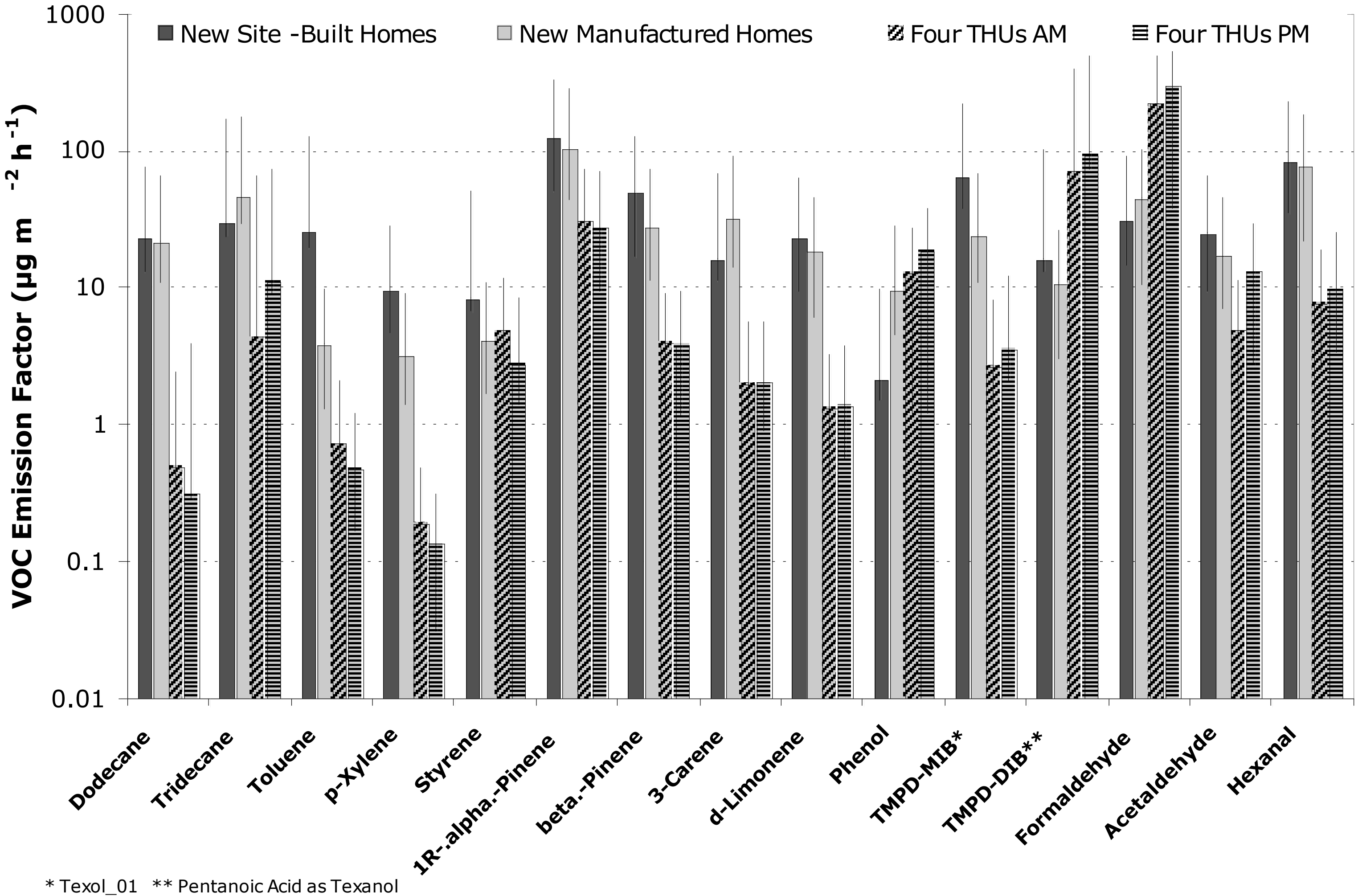

Figure 5. Comparison of GM (GSD error bars) measured whole building VOC emission factors (emissions per floor area) for seven new site built houses, four new manufactured houses (Hodgson et. al. 2000), and the four THUs studied in this project reported for AM and PM sampling events. Note that this chart is plotted on a logarithmic scale.